Maastricht University

Basics of Symmetric Cryptography

Bart Mennink

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Keyed Symmetric Cryptography

General Setting

- Two parties, Alice and Bob, communicate over a public channel
  - We assume they have agreed on a joint key K and use it to transmit data

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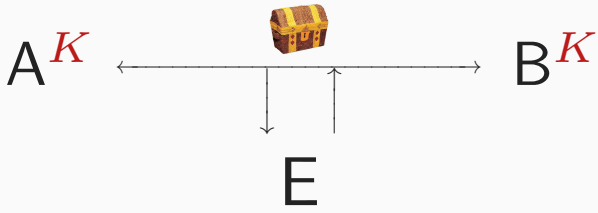

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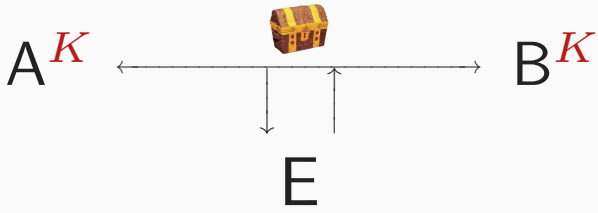

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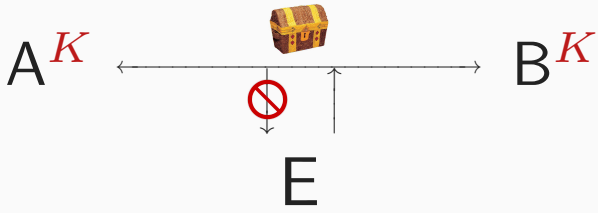

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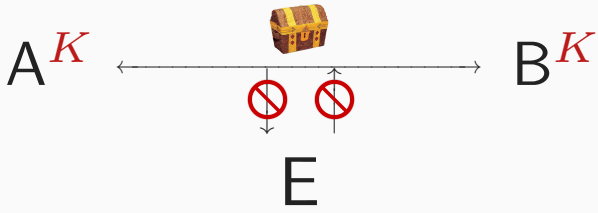

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- Two main security properties:
  - Confidentiality: Eve cannot learn anything about the content of the data
  - Authenticity: Manipulation/replay/delay of the data gets detected

Encryption

One-Time-Pad Encryption

Encryption:

$$P = \begin{array}{cccccccccccccccc} 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \end{array}$$

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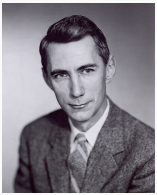
Stream Ciphers

- Generate long keystream Z from short key K



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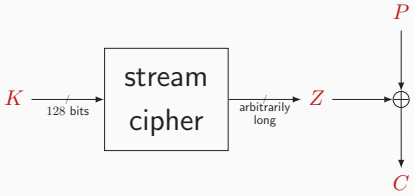

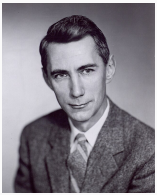

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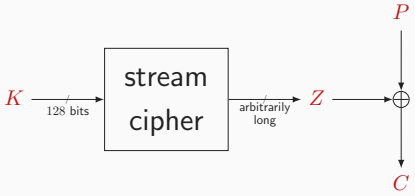

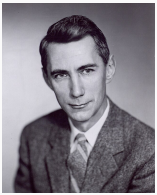

- Security degrades:
  1. Key guessing still succeeds with probability $1/2^{|K|}$ but now with shorter key
  2. The stream cipher mechanism is another focal point of attack

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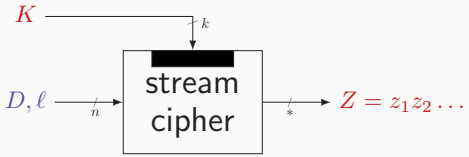
We need something more sophisticated!

Modern Stream Ciphers



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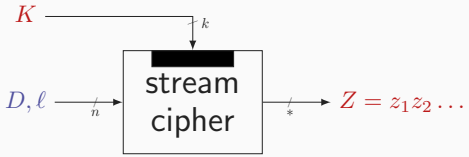

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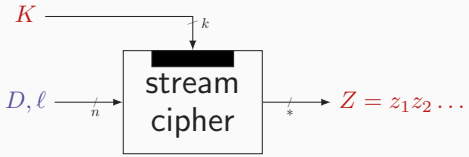

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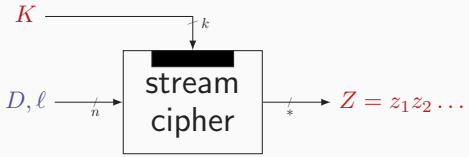

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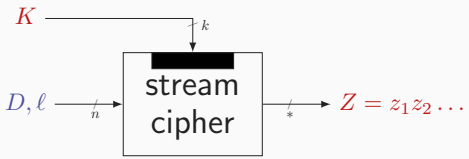

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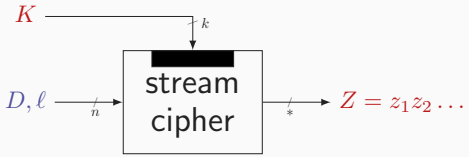

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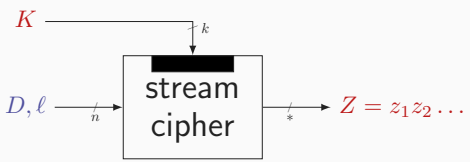

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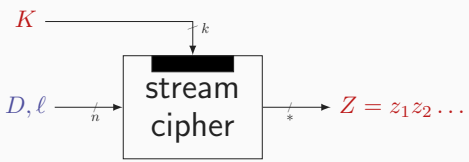

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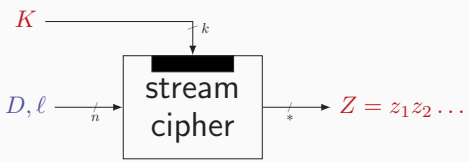

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- SC_K should behave like a random oracle

Intermezzo: Random Oracle

Random Oracle

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...	...
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    - update (D, Z) in the list

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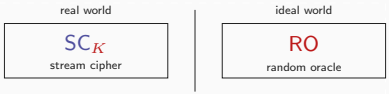
...	...

Stream Cipher Security, Intuition (2/3)



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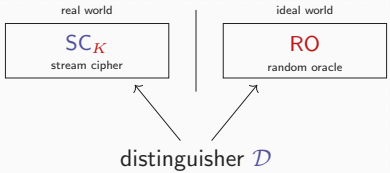

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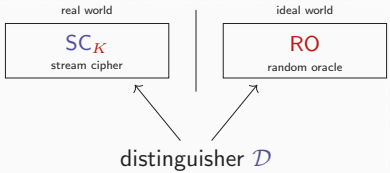

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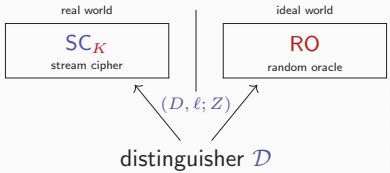

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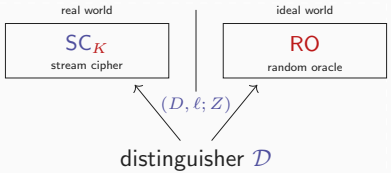

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  - At the end, $\mathcal{D}$ has to guess the outcome of the toss coin (head/tail)

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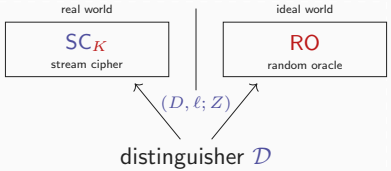

- Denote $\mathcal{D}$'s success probability in correctly guessing head/tail by $\mathbf{Pr}\,(\text{success})$

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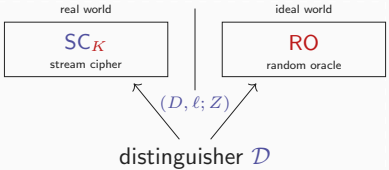

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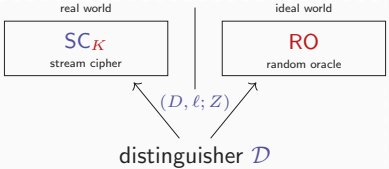

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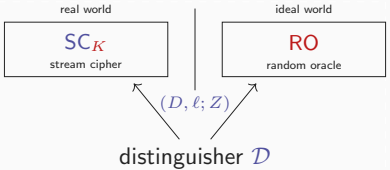

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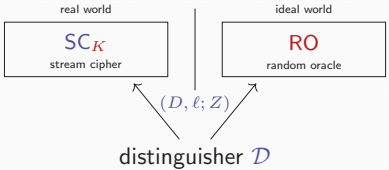

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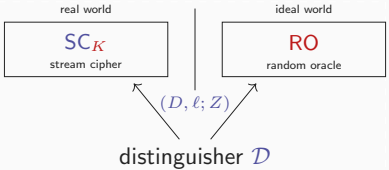

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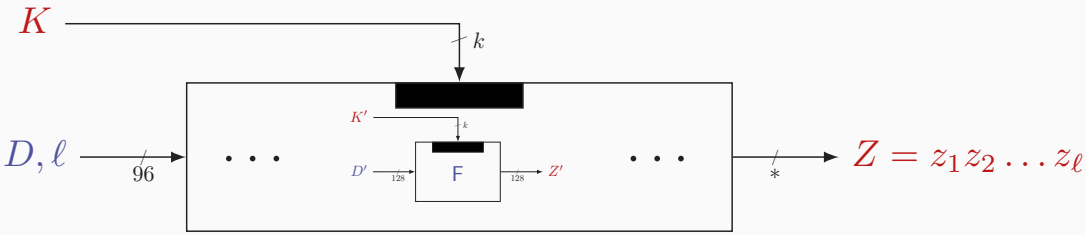

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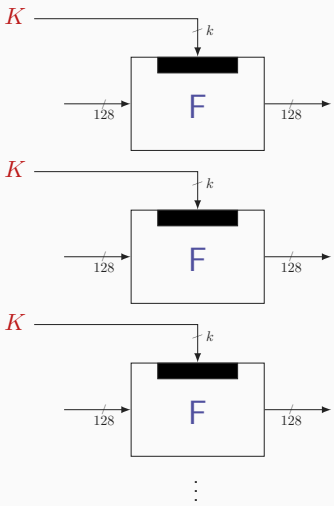

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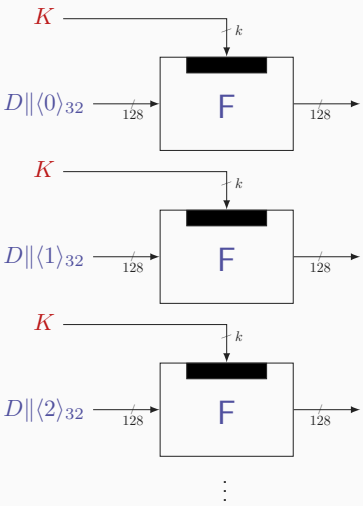

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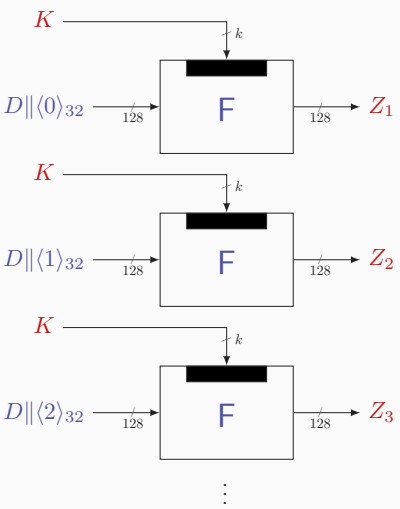

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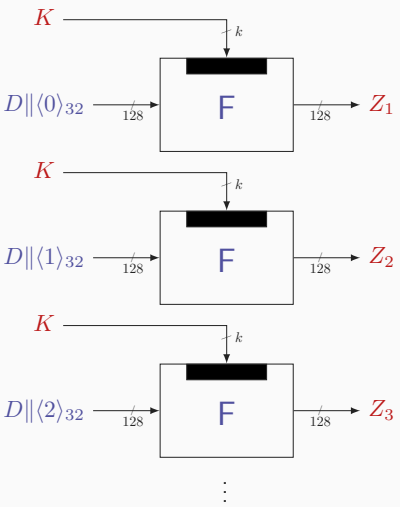

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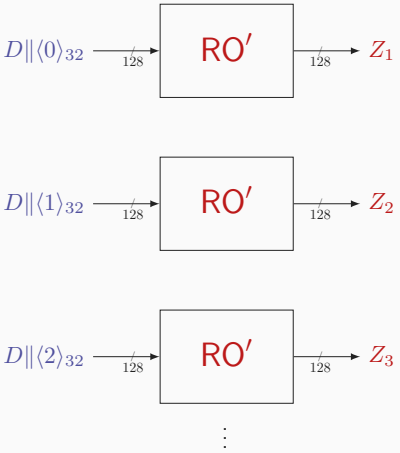

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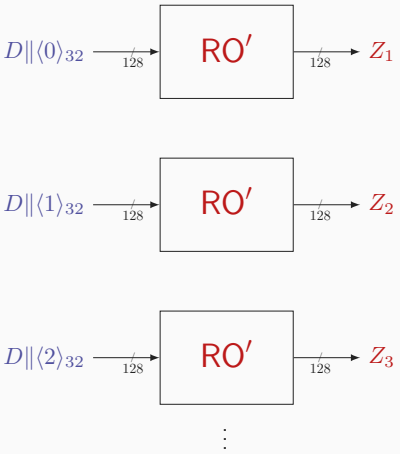

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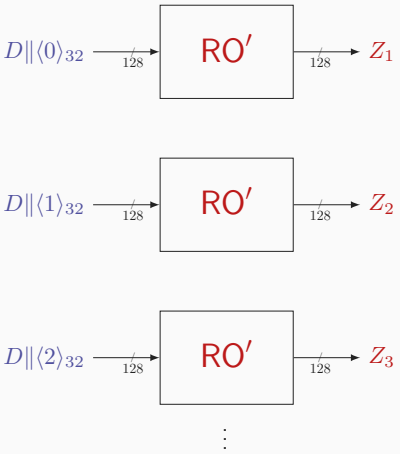

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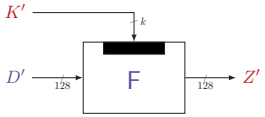
$$Z = Z_1$$

Unfortunately, we do not know how to easily construct a function



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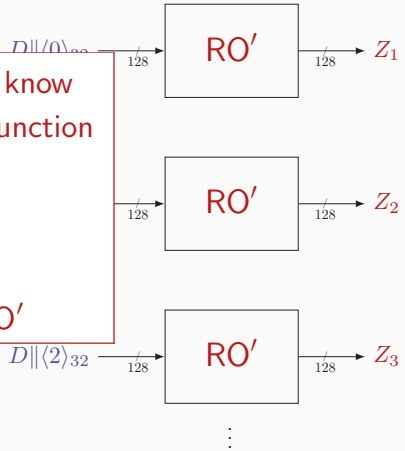

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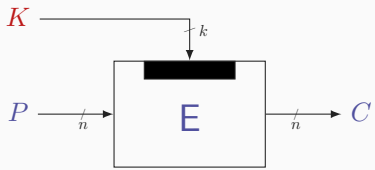
Block Ciphers and AES

Block Ciphers



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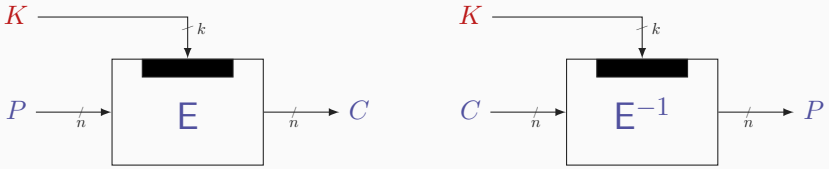

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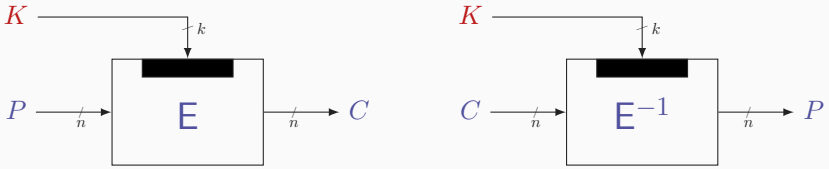

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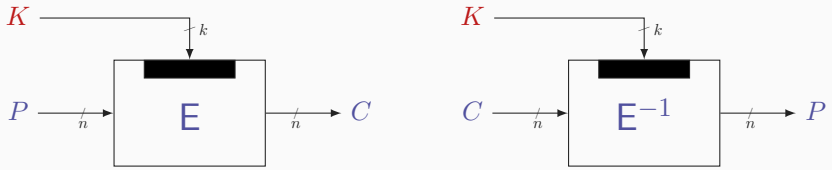

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- A good E should behave like a random permutation if one does not know K

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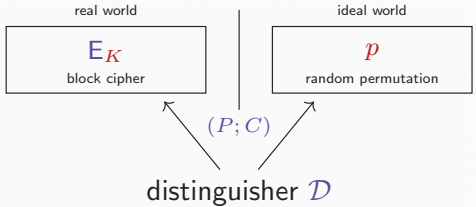

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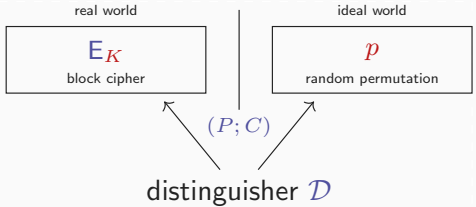

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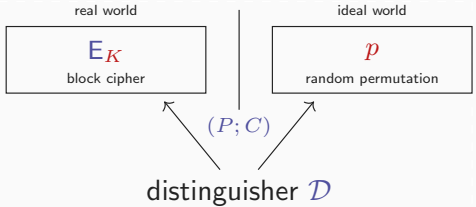

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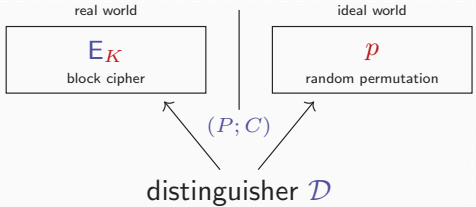

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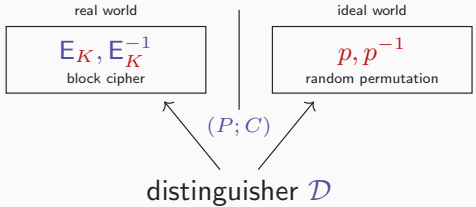

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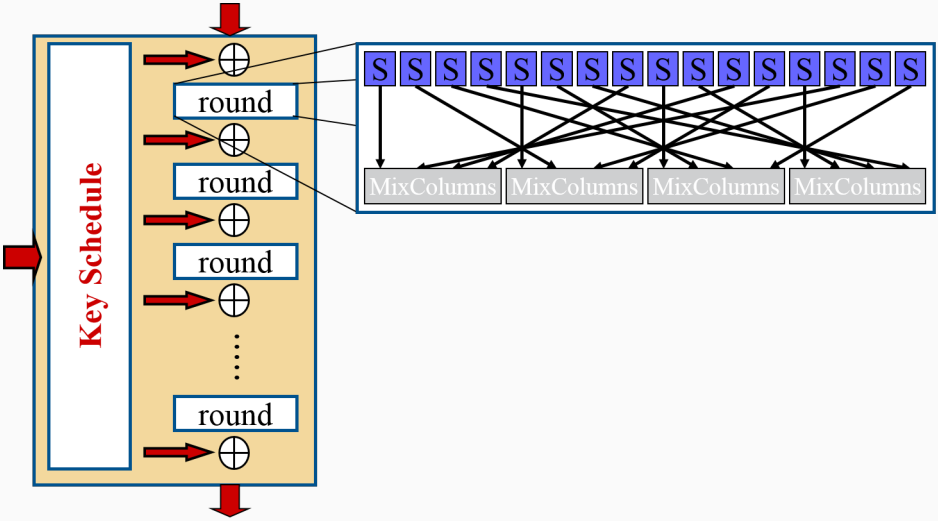
- Extension to SPRP security: $\mathcal{D}$ gets both forward and inverse query access

AES in a Nutshell



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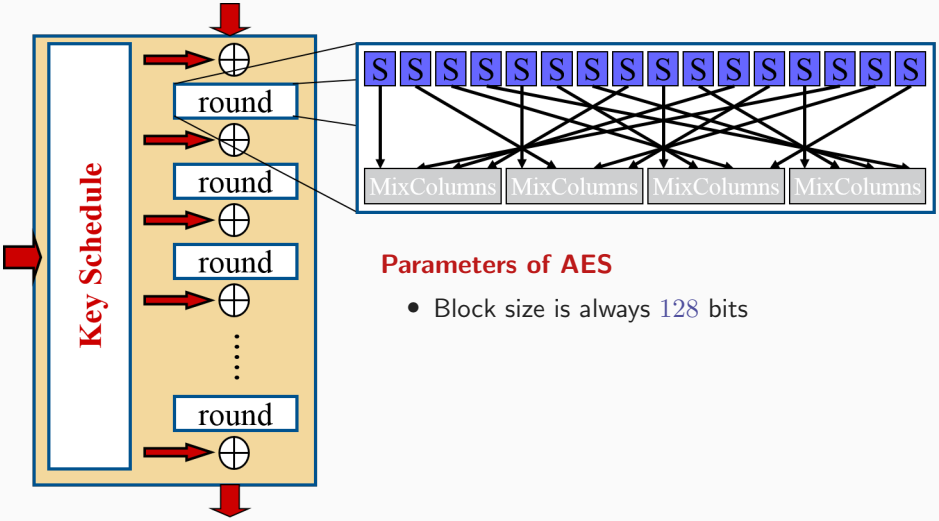

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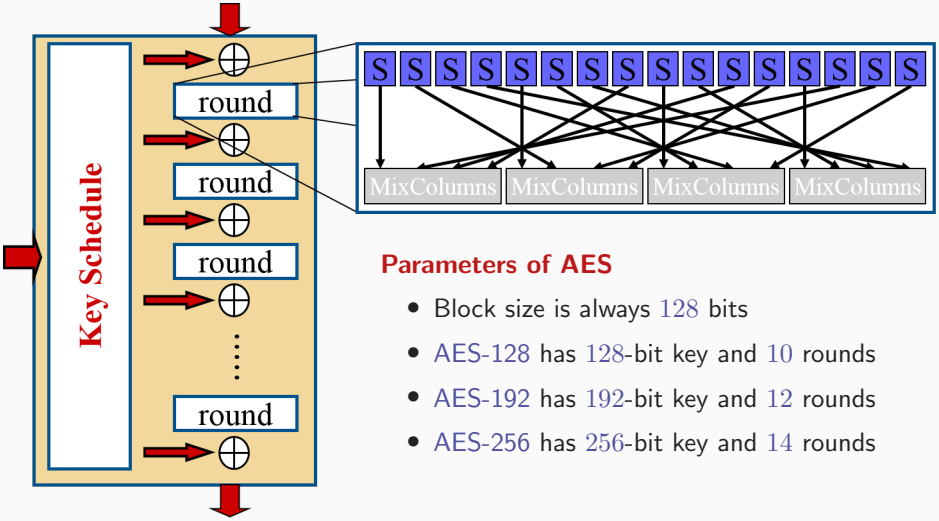

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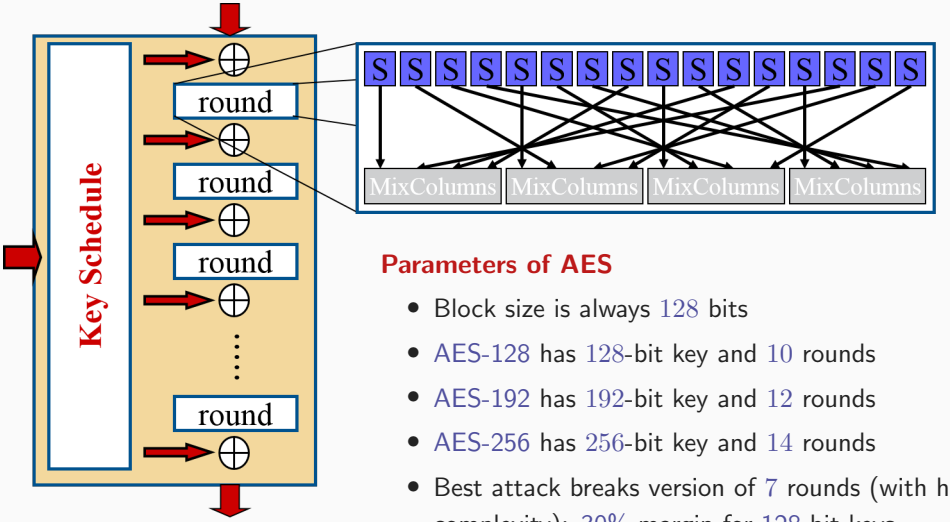

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- For any distinguisher $\mathcal{D}$ with q queries and t time,

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Bottom Line: Don't Worry, Be Happy!

Encryption (continued)

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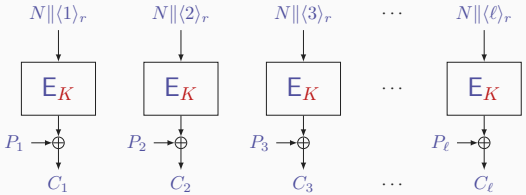

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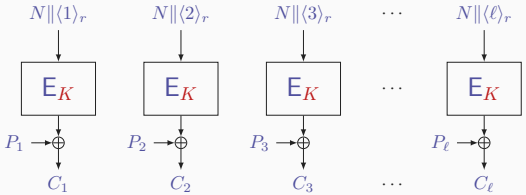

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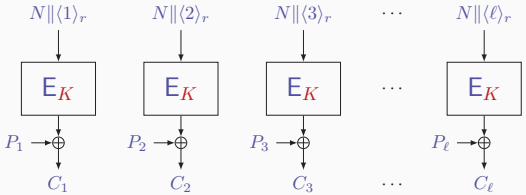

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$$\mathbf{Adv}^{\mathrm{prf}}_{\mathsf{CTR}}(q,t) \leq \mathbf{Adv}^{\mathrm{prp}}_{\mathsf{E}}(q,t') + \binom{q}{2}/2^n$$

birthday bound

General Birthday Paradox

- Randomly draw q elements from sample space $\{0,1\}^n$
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Lightweight Cryptography

- AES has block size of 128 bits: birthday paradox problem only in certain settings
- Lightweight cryptography operates in constrained environments
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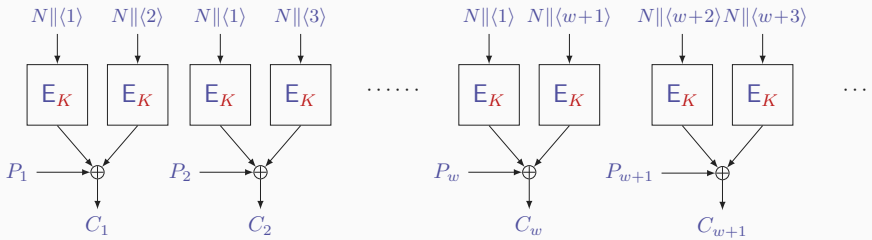
- Lightweight block ciphers have a block size of 64 bits or even less [BKL+07]

CENC [Iwa06]



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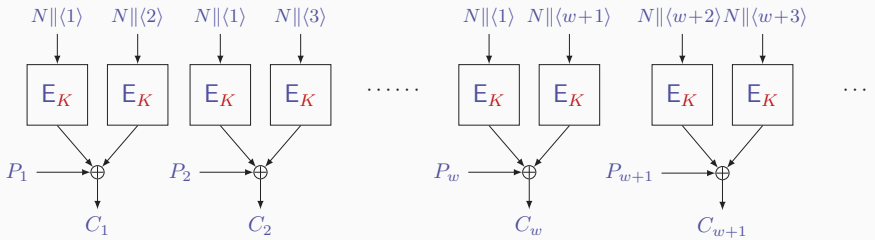

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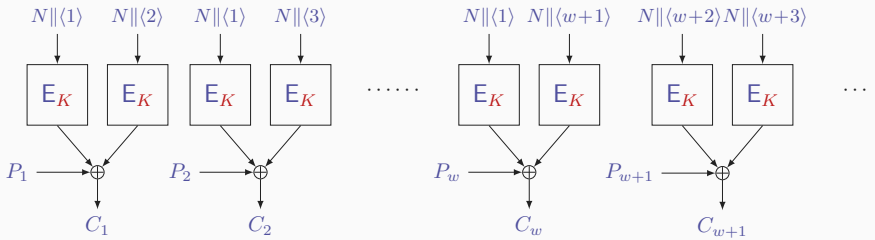

- One subkey used for $w \geq 1$ encryptions
- Almost as expensive as CTR
- Secure as long as N is unique, E_K is a secure PRP, and $q \ll 2^n/w$ [IMV16]:

$$\mathbf{Adv}^{\mathrm{prf}}_{\mathsf{CENC}}(q,t) \leq \mathbf{Adv}^{\mathrm{prp}}_{\mathsf{E}}((w+1)q,t') + wq/2^n$$

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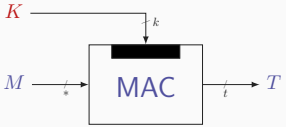

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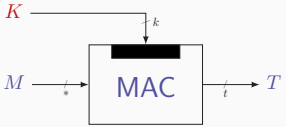

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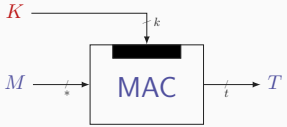

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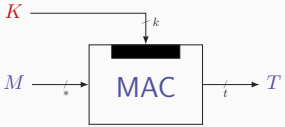

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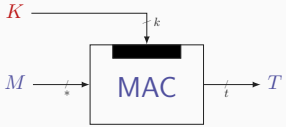

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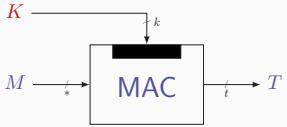

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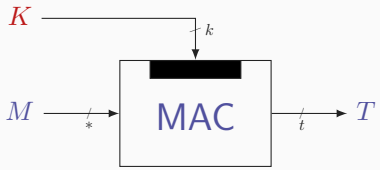
- Often, Bob wants to authenticate more, requiring *active checks* from her part



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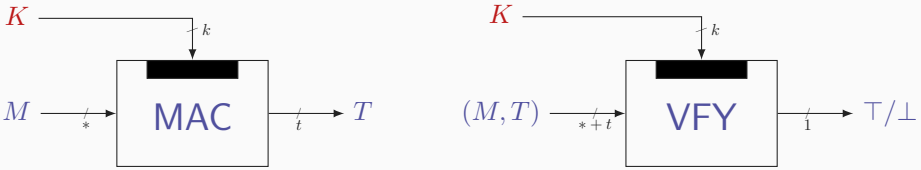

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  - $\top$ if tag is correct
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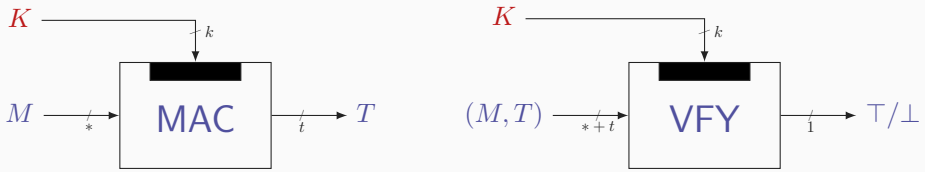

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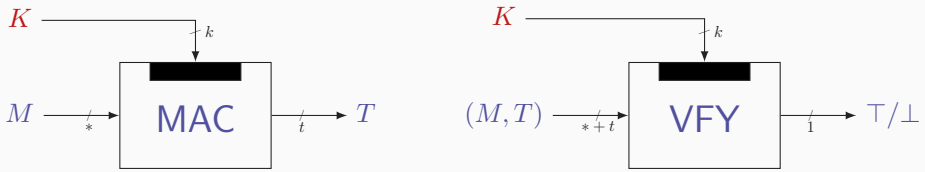

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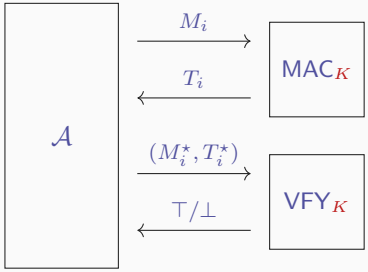
- PRF security implies a weaker notion, called unforgeability

- MAC security defined using unforgeability



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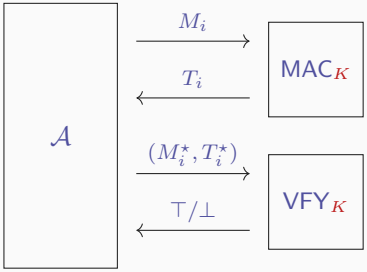

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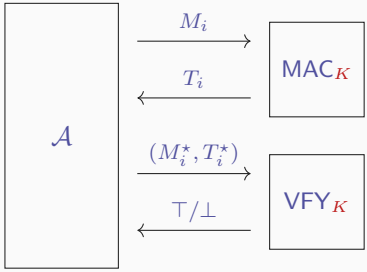

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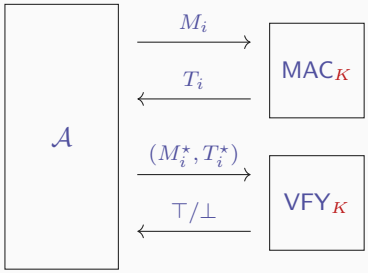
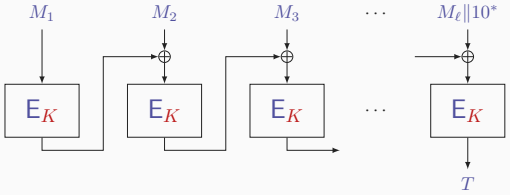
- Its advantage is defined as:

$$\mathbf{Adv}^{\mathrm{unf}}_{\mathsf{MAC}}(\mathcal{A}) = \mathbf{Pr}\left(\mathcal{A}^{\mathsf{MAC}_K,\mathsf{VFY}_K} \text{ forges}\right)$$

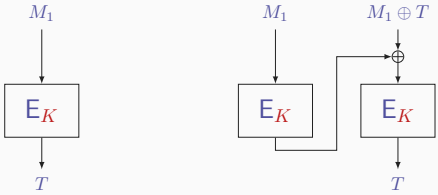


Cipher Block Chaining MAC (CBC-MAC): MAC Function From Block Cipher



- Apply E_K to first block of padded message M_1 to give initial CV
- Absorb message block M_i in CV by computing $CV \leftarrow \mathsf{E}_K(CV \oplus M_i)$
- Tag T is the final value of CV

Cipher Block Chaining MAC (CBC-MAC): Weakness



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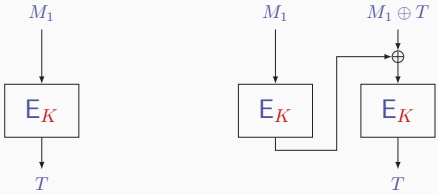

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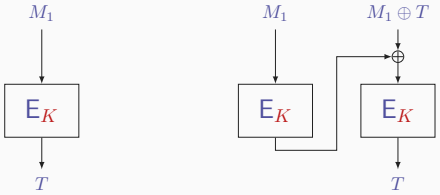

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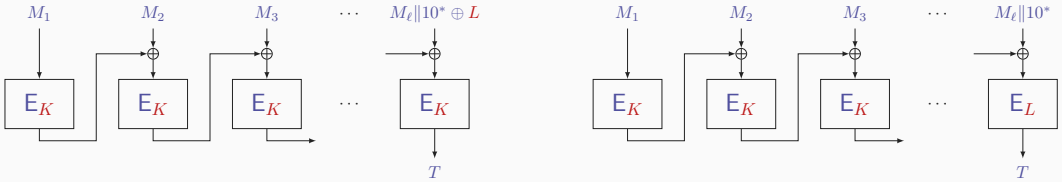
- Note: attack ignores padding, but this can be dealt with

CBC-MAC(-like): MAC Function From Block Cipher



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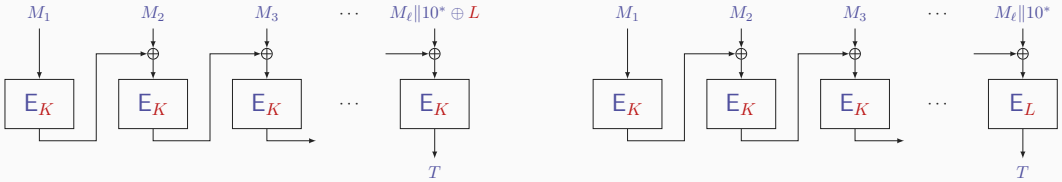

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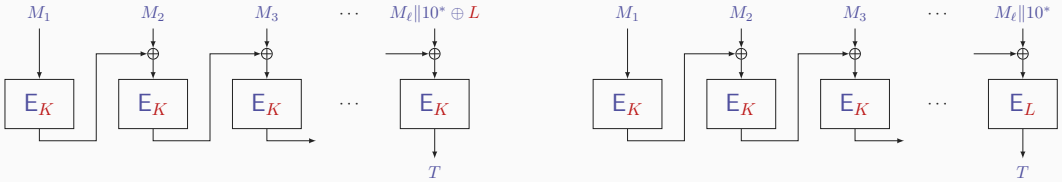

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- Secure if E_K behaves like a random permutation
- Security again only up to the birthday bound: $2^{n/2}$ blocks

But Wait, Quantum Period Finding!

Simon's Algorithm [Sim97]

- Period finding can be done in polynomial time
- C-MAC permits a period and can be broken in $O(n)$ time [KLLN16]

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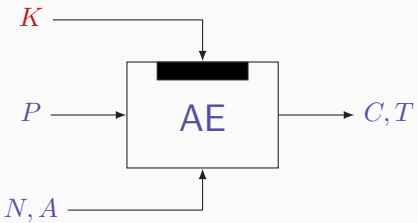
Bottom Line: Don't Worry, Be Happy!

Authenticated Encryption and GCM

Authenticated Encryption (AE): Wrap



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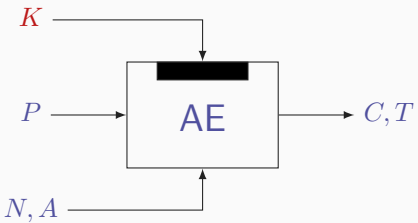

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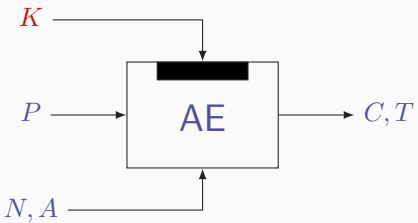

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- There exist AE schemes that are secure without a nonce: more expensive

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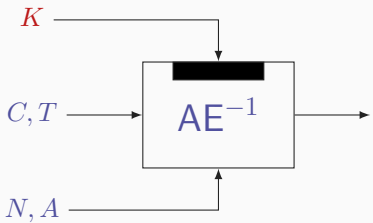

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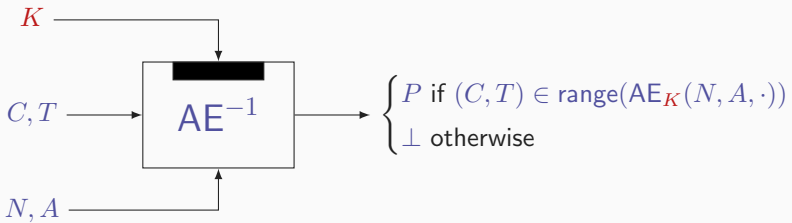

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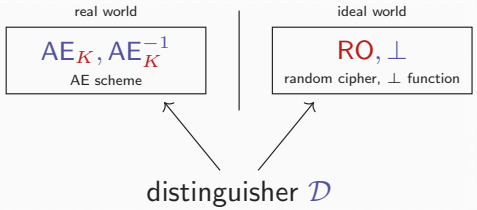

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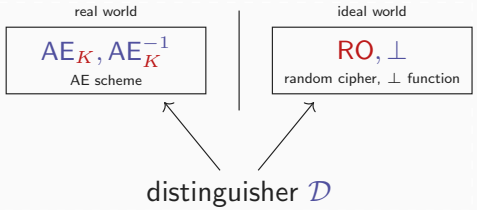

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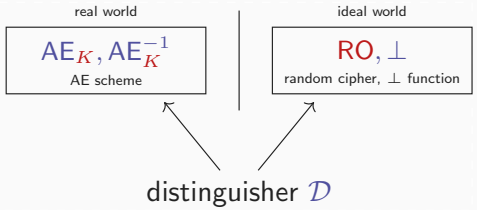

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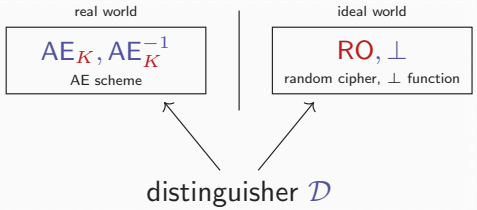

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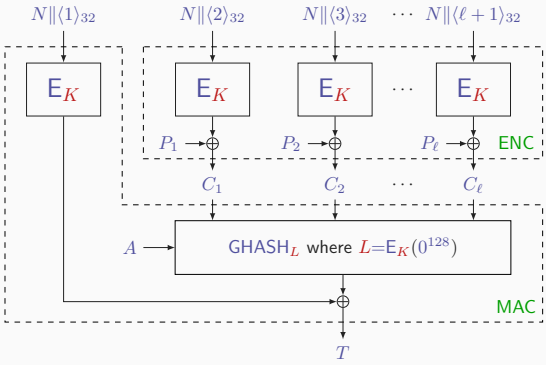
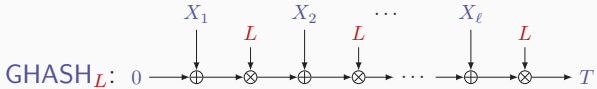
$$\mathbf{Adv}^{\mathrm{ae}}_{\mathsf{AE}}(\mathcal{D}) = \left| \mathbf{Pr}\left(\mathcal{D}^{\mathsf{AE}_K, \mathsf{AE}_K^{-1}} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\mathsf{RO}, \perp} = 1\right) \right|$$

GCM for 96-bit Nonce N [MV04]





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- Efficient, parallelizable, inverse-free
- Widely used:
  - TLS, WPA3, IPsec, ...
- Cooler variant: ChaCha20-Poly1305!

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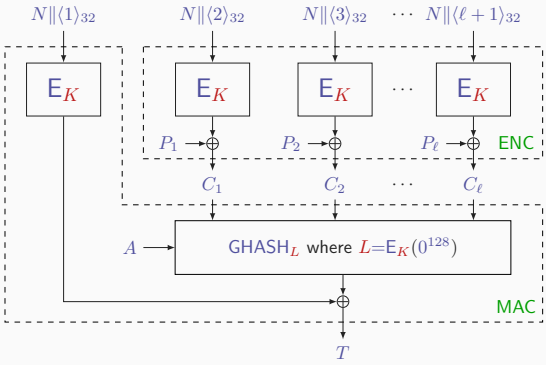

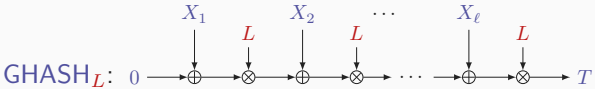

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- Number of blocks doesn't exceed $2^{n/2}$
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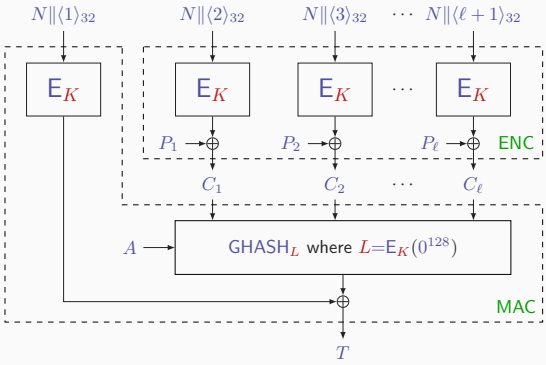

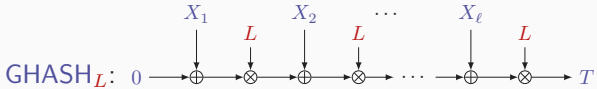

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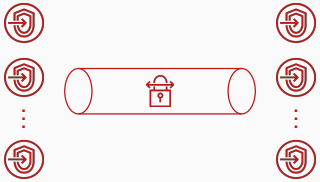
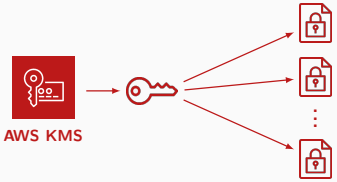
- ... but nonce reuse is devastating
  - Leaks $P \oplus P' = C \oplus C'$ and L

Problems With GCM for 96-bit Nonce N

Use Case: Amazon Web Services [KCCP23]



AWS distributed systems encrypt
up to $\approx 2^{32}$ plaintexts per 2 seconds



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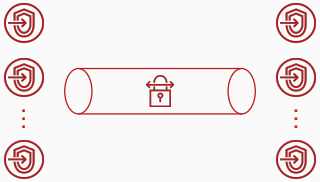

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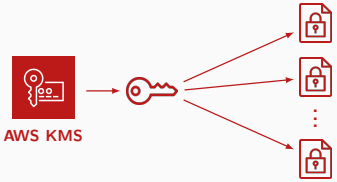

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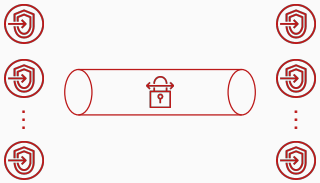

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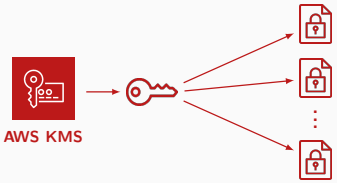

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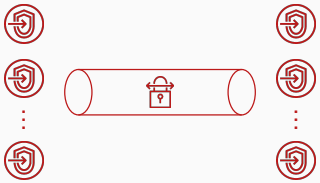

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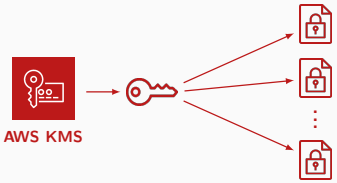

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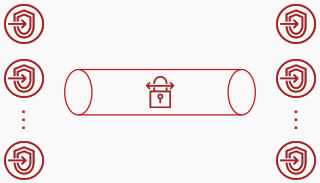

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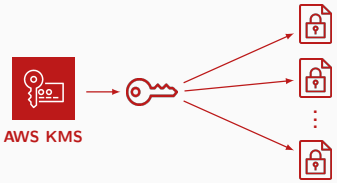

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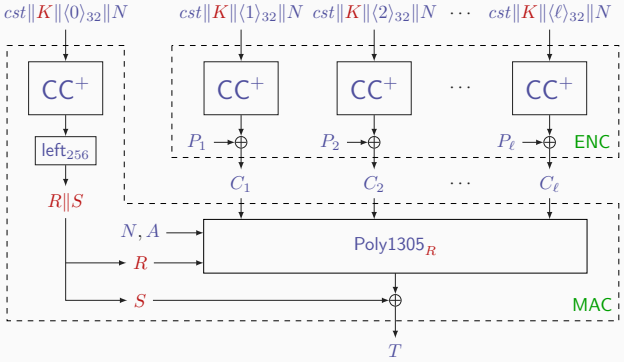
- AWS also needs 32-bit identifiers, leaving only 64 bits of nonce
- Limitations of GCM are a real world problem!

ChaCha20-Poly1305



- Bernstein [Ber05, Ber08]
- RFC 8439 [NL18]

- CC: 512-bit permutation
- CC$^+$: CC plus feed-forward

$$\text{Poly1305}_R(X) = (1\|X_1)\cdot R^\ell + (1\|X_2)\cdot R^{\ell-1} + \cdots + (1\|X_{\ell-1})\cdot R^2 + X_\ell \cdot R \bmod 2^{130} - 5$$

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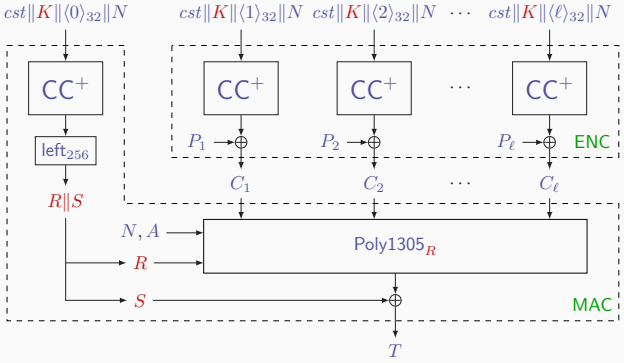

- Bernstein [Ber05, Ber08]
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- CC: 512-bit permutation
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- Both key and mask of Poly1305 are nonce-dependent

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- Certain use cases expose limitations of current standards

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Thank you for your attention!

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