Automated Analysis and Synthesis of Authenticated Encryption Schemes

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Authenticated Encryption (AE)

Sender → **Receiver**

K K

Privacy **Authenticity**

Encryption scheme

Authenticated Encryption:
Achieve **both** of these aims

Message Authentication Code (MAC)

Authenticated Encryption (AE)

- Lots of AE schemes
  - OCB, CCM, CAESAR candidates, etc.

Authenticated Encryption (AE)

- Lots of AE schemes
  - **OCB**, CCM, CAESAR candidates, etc.

    ✓ Most efficient
    ✘ Patented

Authenticated Encryption (AE)

- Lots of AE schemes
  - OCB, **CCM**, CAESAR candidates, etc.

✓ Not patented
✘ Slower than OCB

Authenticated Encryption (AE)

- Lots of AE schemes
  - OCB, CCM, **CAESAR candidates**, etc.

Ongoing competition
for new AE standard
$\rightarrow$ Active area of research

Authenticated Encryption (AE)

- Lots of AE schemes
  - OCB, CCM, CAESAR candidates, etc.

- Developing new AE schemes is hard
  - Complex, error-prone proofs

More systematic way to build secure AE schemes?

Our approach

based on *tweakable blockciphers*

Automatically ***analyze*** and ***synthesize*** AE schemes

Extend [MalozemoffKatzGreen14], which analyzed / synthesized *encryption modes of operation*

Captures many existing schemes:
OCB, XCBC, COPA, OTR, CCM, etc.

Our approach

Step 1: View AE scheme as graphs

- **Nodes**: operation (e.g., E_K, $\oplus$)
- **Edges**: Intermediate values

Step 2: Construct type system for graphs

- Typed graphs $\implies$ secure AE scheme

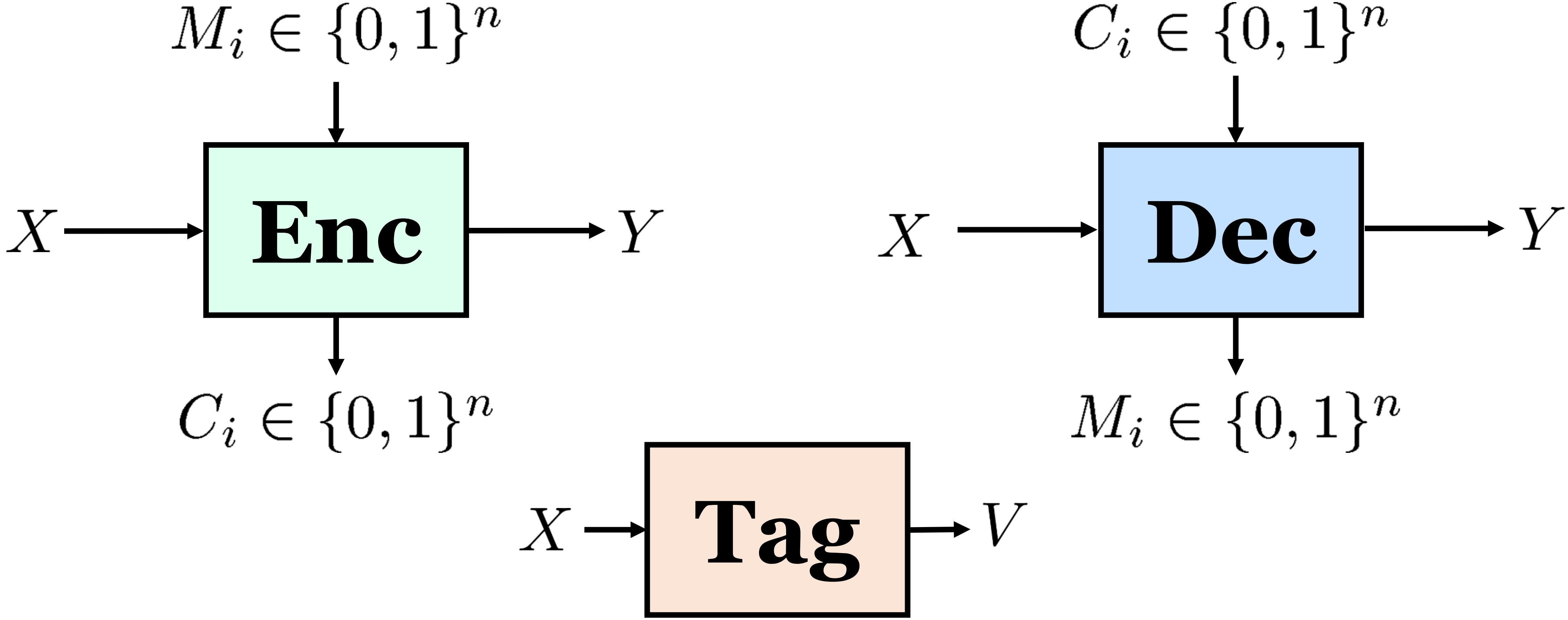
Step 3: Synthesize AE schemes using type system

Outline of rest of talk

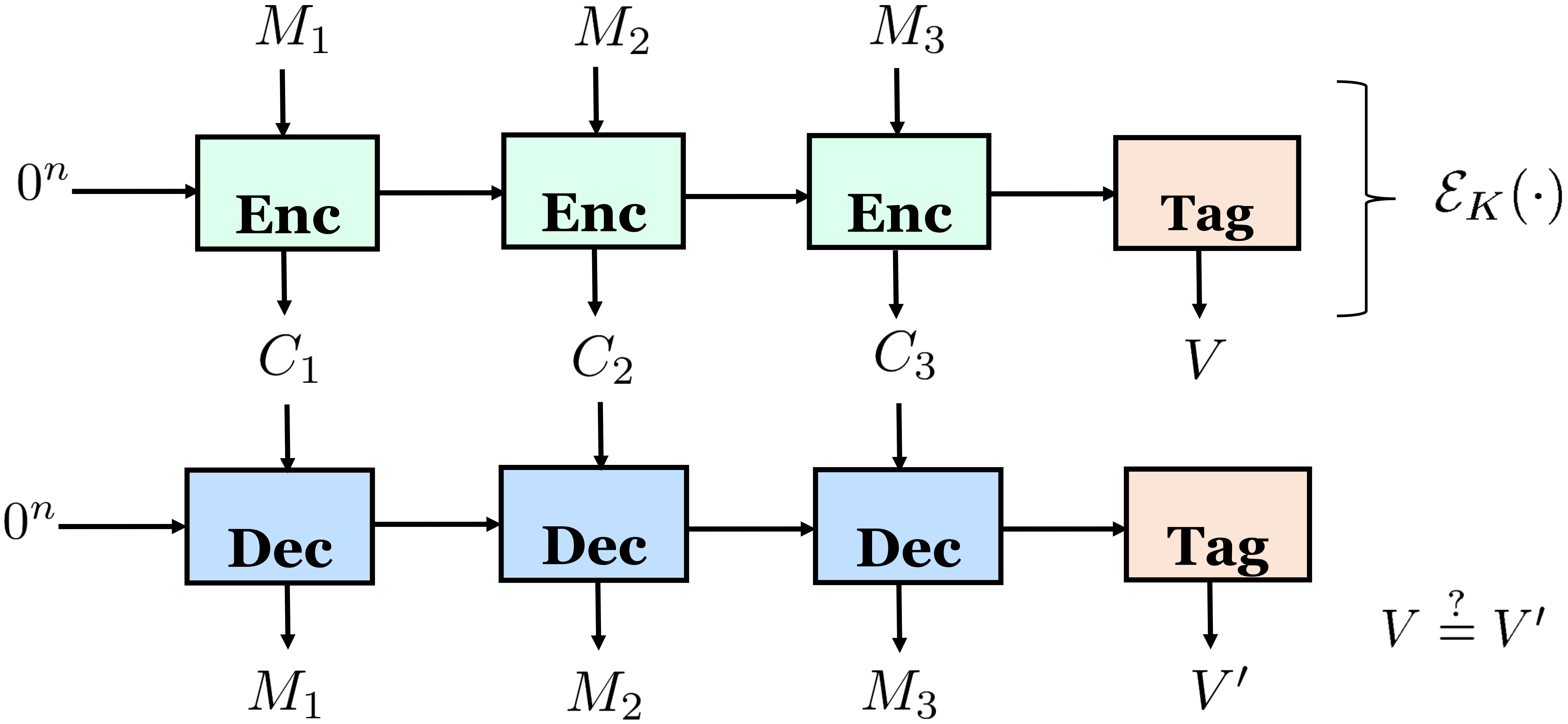
1. Template for AE schemes
2. Viewing AE schemes as graphs
3. Type system for graphs
4. Implementation + results

Template for AE schemes

AE scheme defined by three algorithms:
Enc, **Dec**, **Tag**



Template for AE schemes

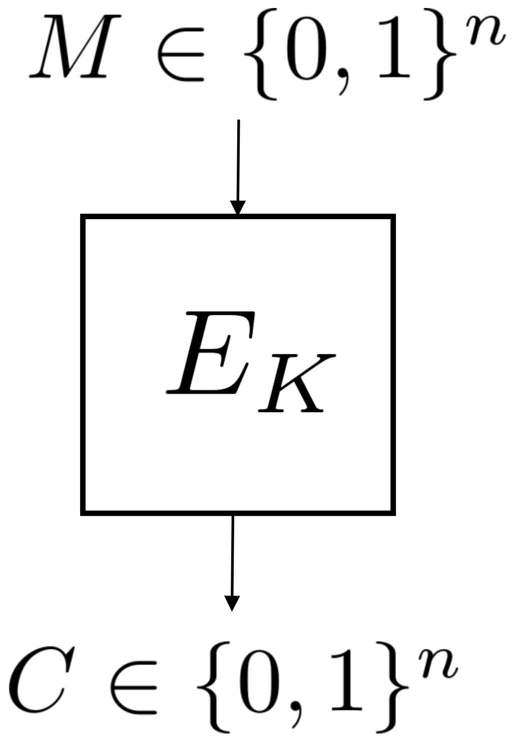


Note: Ignoring nonce/associated data

Restricted class of AE schemes

Consider AE schemes using *tweakable blockciphers (TBCs)*

(Standard) blockcipher:

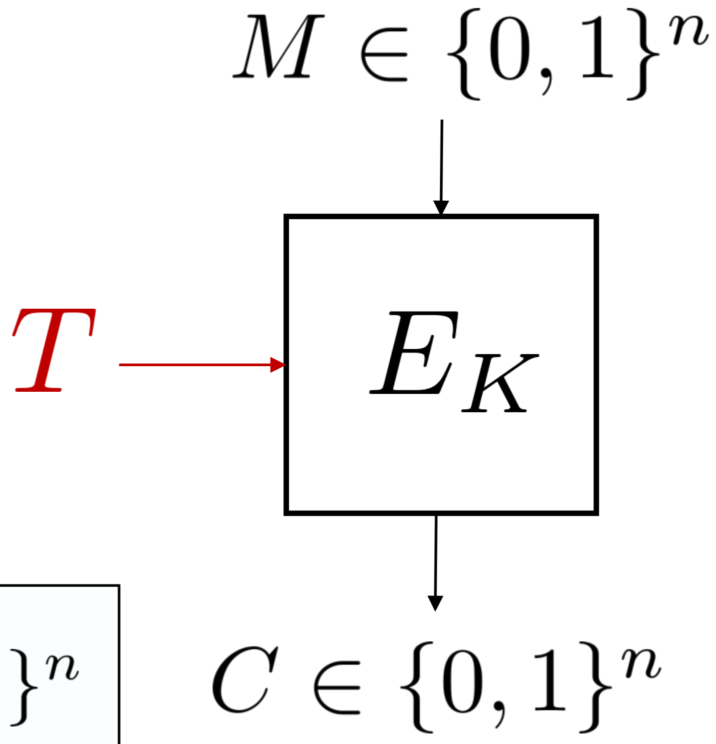


E_K: Permutation on $\{0,1\}^n$

Restricted class of AE schemes

Consider AE schemes using *tweakable blockciphers (TBCs)*

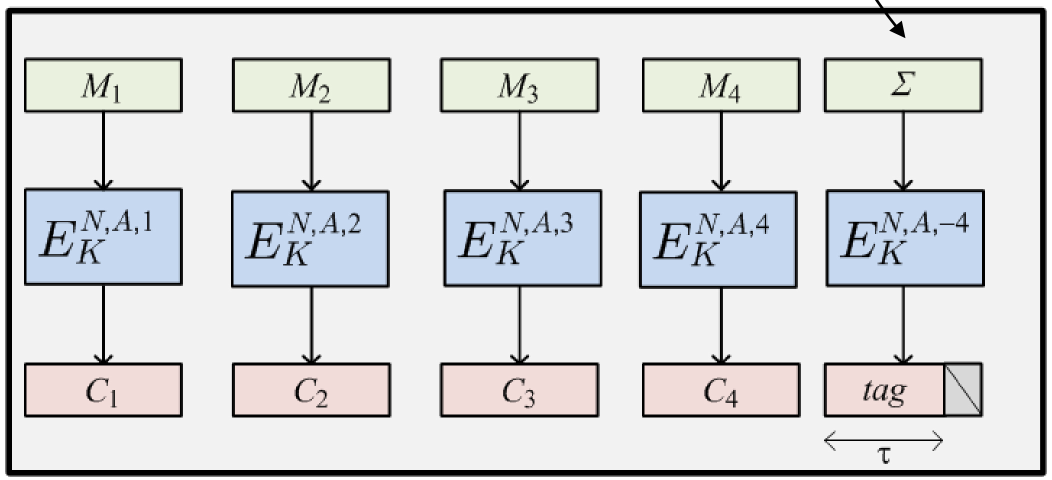
Tweakable blockcipher:

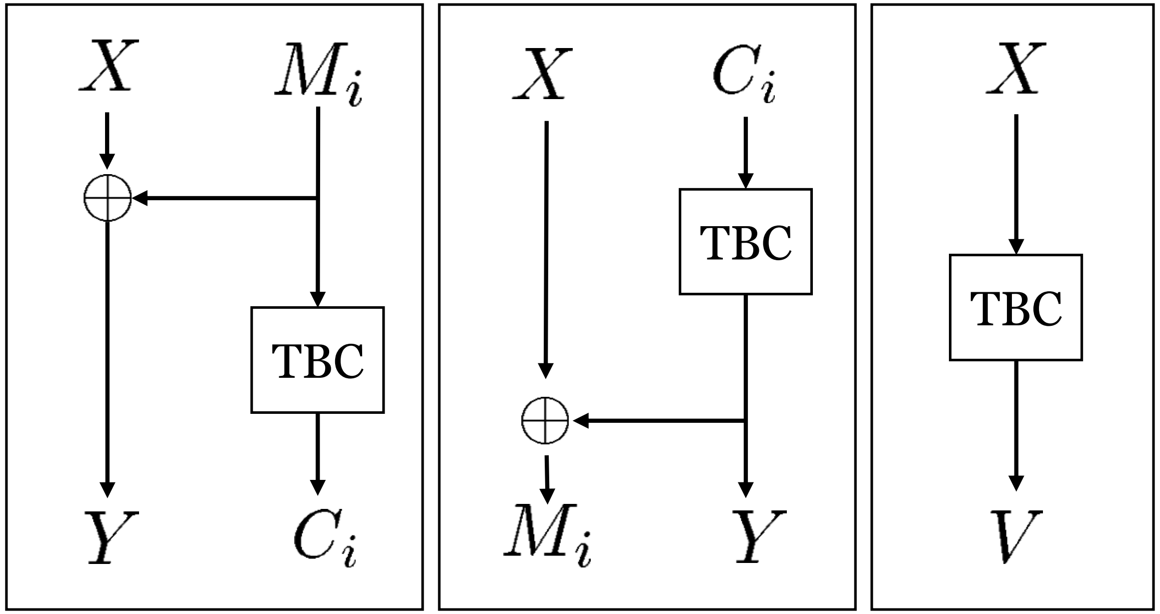


E_K^T: Permutation on $\{0,1\}^n$

Example AE scheme using TBCs: OCB

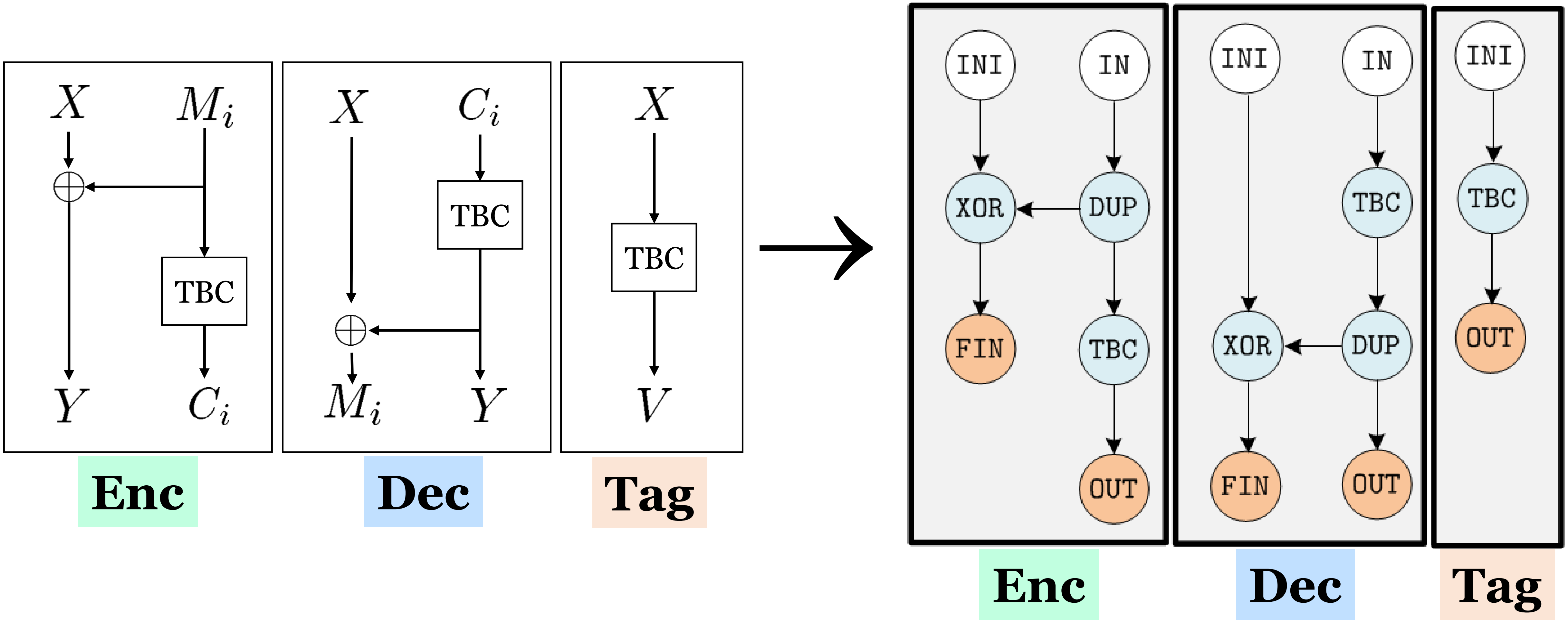
$$\Sigma = M_1 \oplus M_2 \oplus M_3 \oplus M_4$$





Enc **Dec** **Tag**

Viewing AE schemes as graphs



Type system for graphs

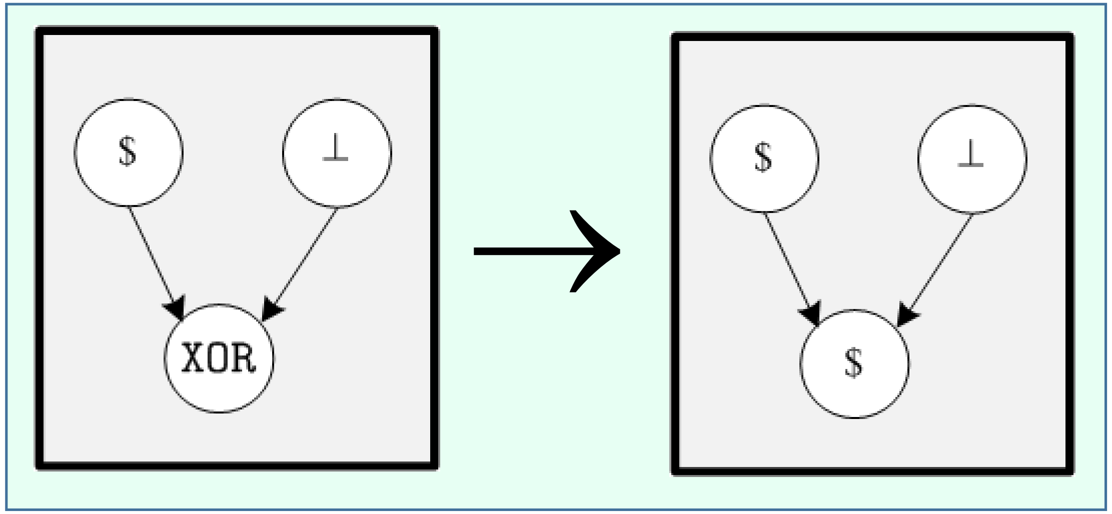
Each **node** assigned ***type*** corresponding to "property" of node output

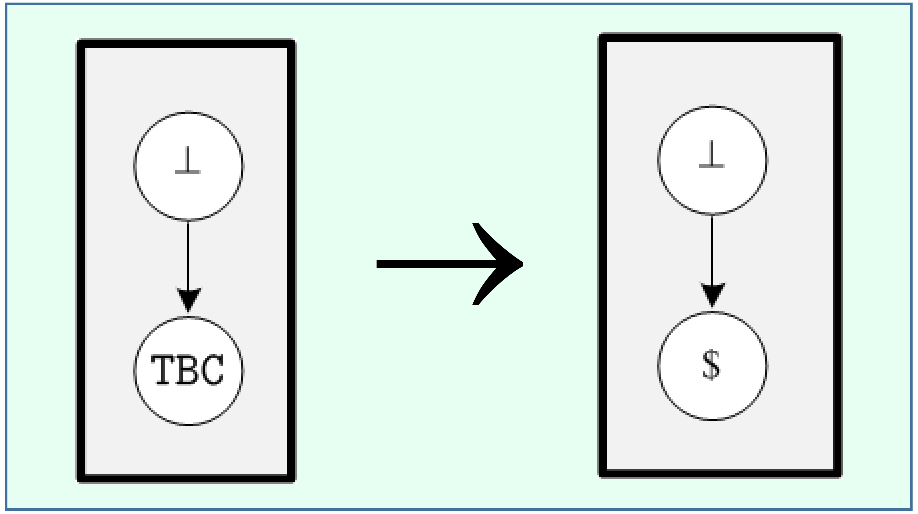
Type = $\{\perp, \$, 0, 1\}$

- $\perp$: "Arbitrary"
- $\$$: "Random"
- 0 and 1: Used in authenticity check (ignore for this talk)

Type system for graphs

Constraints on how nodes can be typed, e.g.:



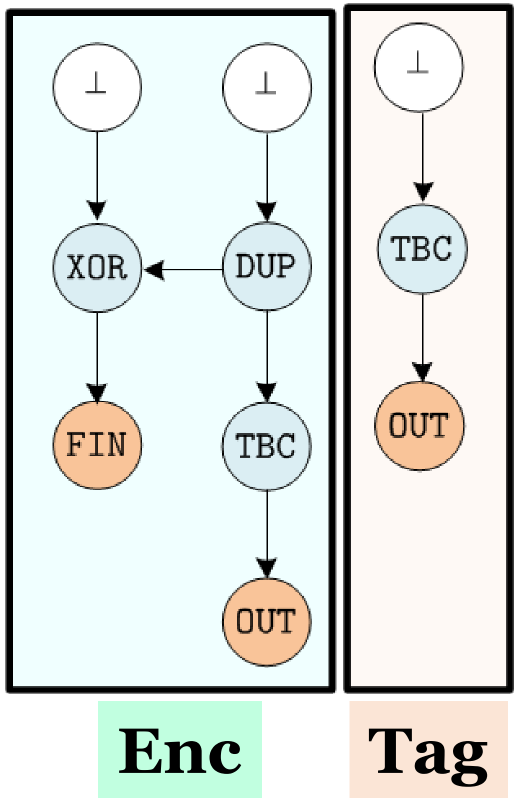


Can show:
Node type \$ $\Rightarrow$ node output is (pseudo)random

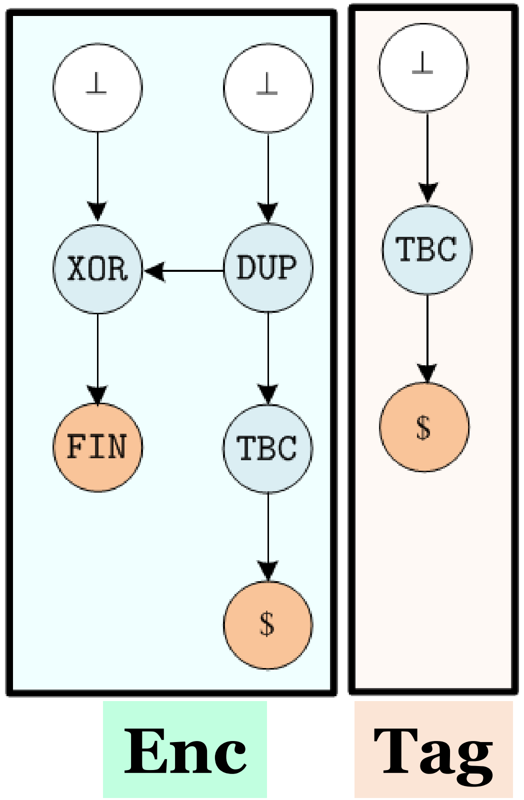
From typed graphs to secure AE schemes

Need to show *two* properties: **privacy** and **authenticity**

Privacy: $\Pr[A^{\mathcal{E}_K(\cdot)} \Rightarrow 1] - \Pr[A^{\$(\cdot)} \Rightarrow 1]$ is small



Goal
$\rightarrow$



From typed graphs to secure AE schemes

Authenticity: $\Pr[A^{\mathcal{E}_K(\cdot)} \text{ forges}]$ is small

valid $C \ (= C_1 \cdots C_\ell V)$

A

C must not be output of some prior query to $\mathcal{E}_K(\cdot)$

Decrypting $C_1 \cdots C_\ell$ produces random tag V'
$\Rightarrow V' \neq V \Rightarrow$ Not valid forgery

Implementation

Implemented *analyzer* and *synthesizer* in OCaml

Analyzer:

(**Enc**, **Tag**) → Derive **Dec** from **Enc** → (**Enc**, **Dec**, **Tag**)

↓

Priv + auth checks

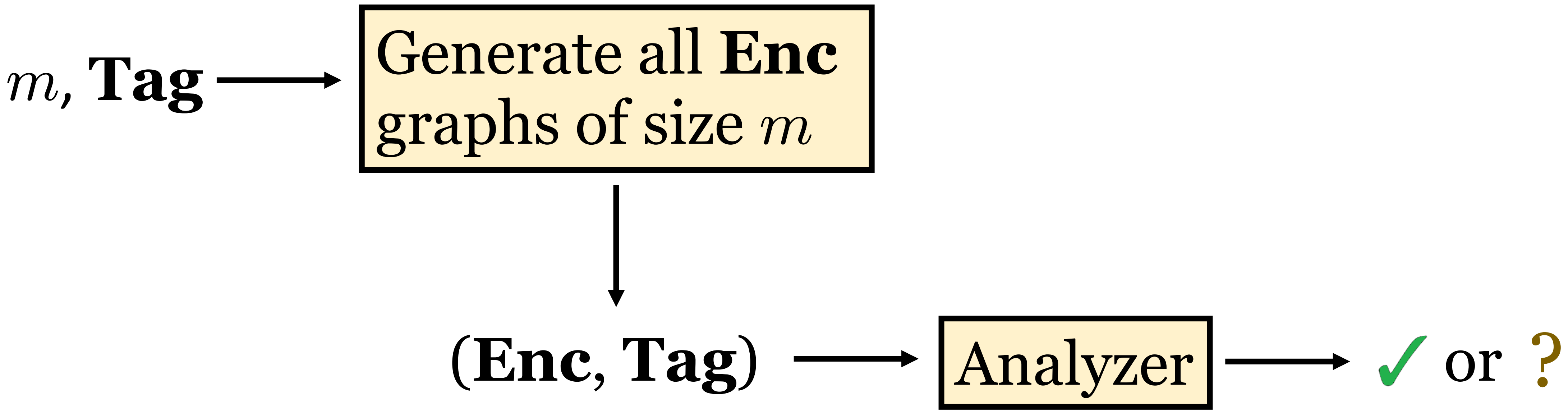
↓

✓ or ?

Implementation

Implemented *analyzer* and *synthesizer* in OCaml

Synthesizer:



Synthesis results

Ran synthesizer for **Enc** graphs of size 12-16…

Size	# Secure	# Optimal	# Parallel	Time
12	13	13	5	47 sec
13	142	0	0	4.3 min
14	582	171	5	24.2 min
15	2826	40	6	2.8 hours
16	3090	66	1	3 hours*
Total	**6653**	**290**	**17**	

- **Optimal**: 1 TBC per message block
- **Parallel**: TBC calls can be parallelized

* = Stopped analysis after given time

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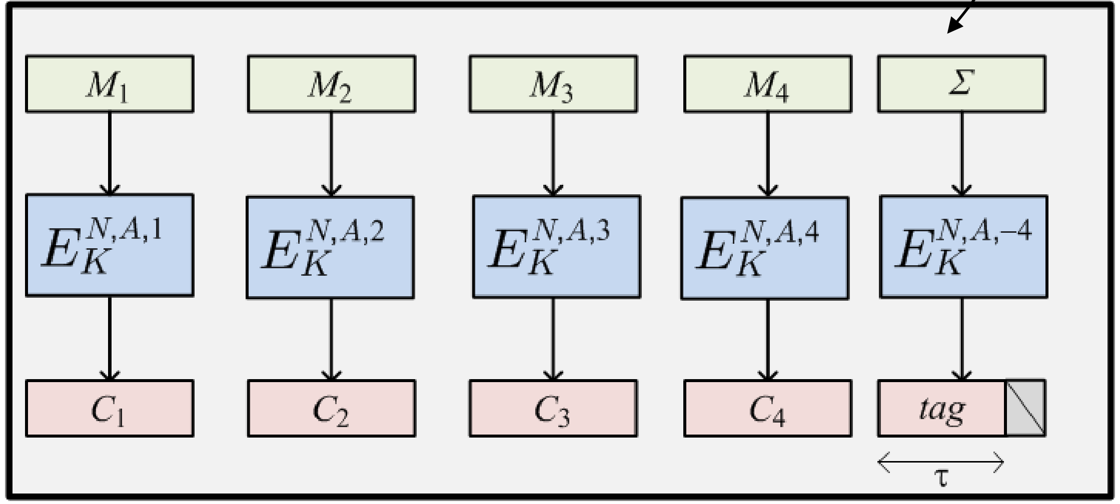
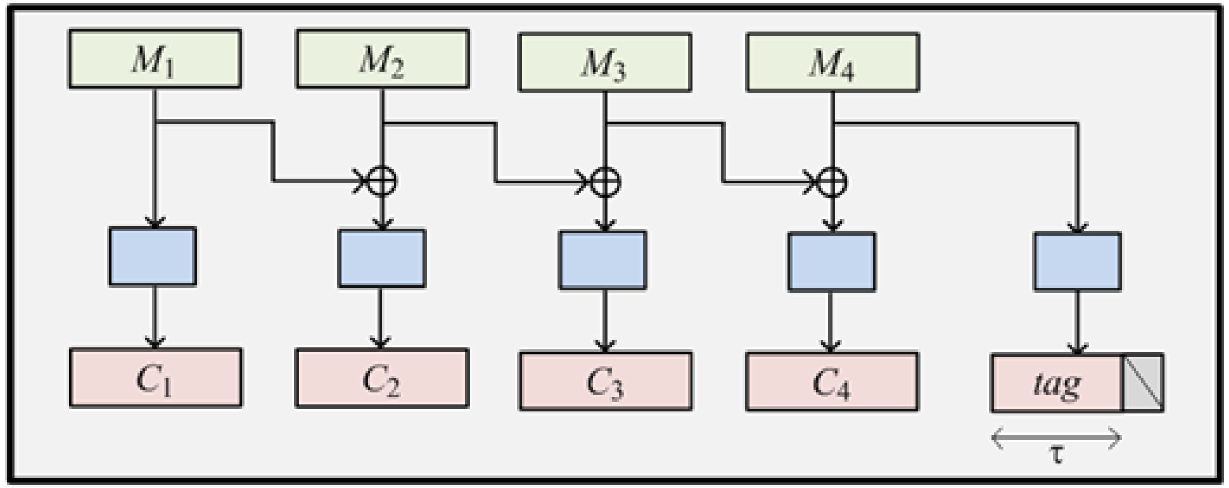
OCB is the only previously known AE scheme of size 12

Example synthesized schemes

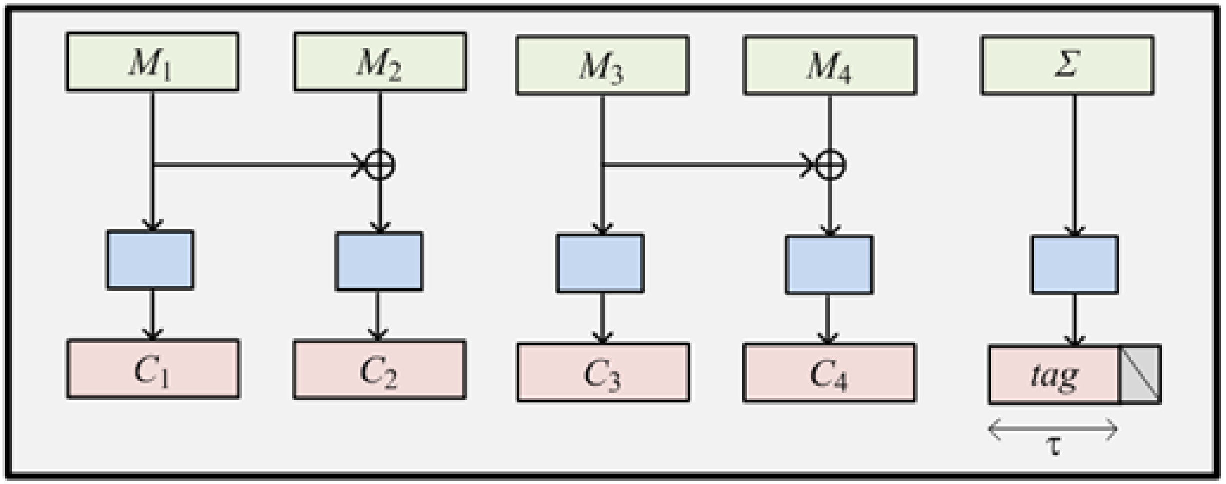
$$\Sigma = M_1 \oplus M_2 \oplus M_3 \oplus M_4$$



OCB



Scheme 1



Scheme 2

Example synthesized schemes: performance

Scheme	Encryption (cpb)	Decryption (cpb)
OCB	0.71	0.76
1	0.72	0.75
2	0.71	0.76

Synthesized novel schemes on par with OCB

Conclusion

- Developed system for automatically *analyzing* and *synthesizing* AE schemes
- Able to synthesize schemes *as efficient and parallelizable as OCB*
- More results (e.g., automated attack generation) in paper

Full Version: https://eprint.iacr.org/2015/624
Code: https://www.github.com/amaloz/ae-generator