THRESHOLD CRYPTOGRAPHY AGAINST COMBINED ATTACKS

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Joint work with Oscar Reparaz, Victor Arribas, Begül Bilgin, Svetla Nikova, Ventzi Nikov, Vincent Rijmen, Nigel Smart

NIST

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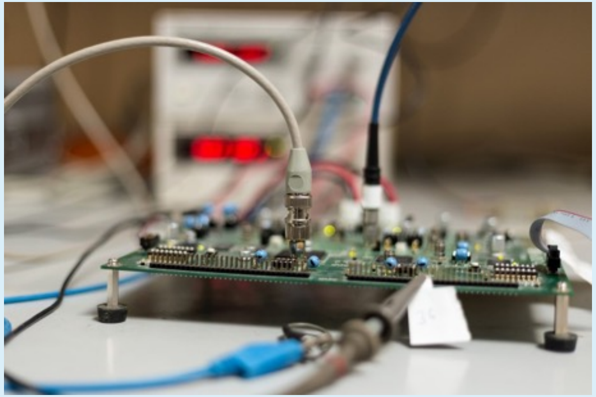
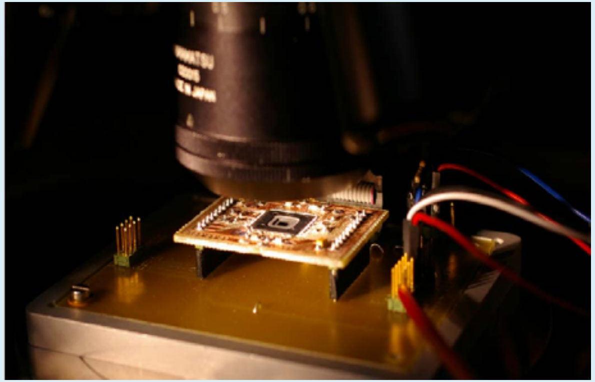
KU LEUVEN





Back to the 90’s

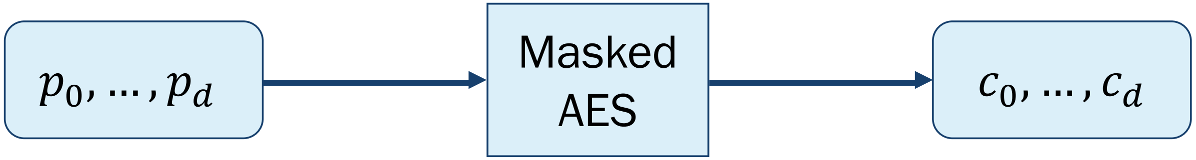
- Differential Power Analysis (DPA) - Paul Kocher 1999 [1]

- Differential Fault Analysis (DFA) - Biham and Shamir 1997 [2]

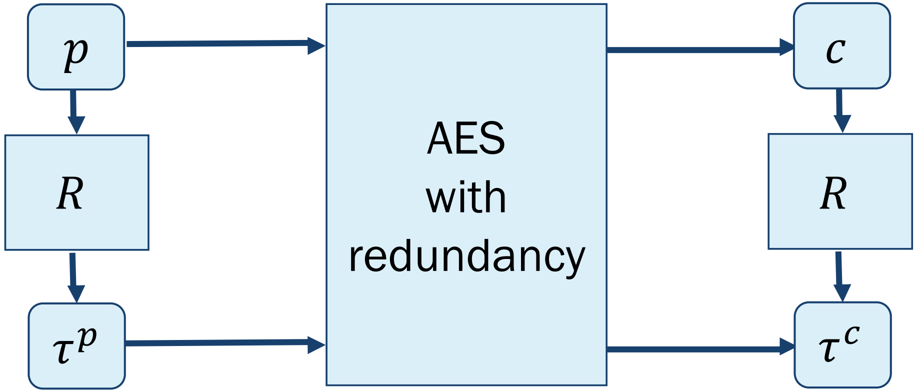
[1] Paul C. Kocher, Joshua Jaffe, Benjamin Jun: Differential Power Analysis. CRYPTO 1999: 388-397
[2] Eli Biham, Adi Shamir: Differential Fault Analysis of Secret Key Cryptosystems. CRYPTO 1997: 513-525

Countermeasures

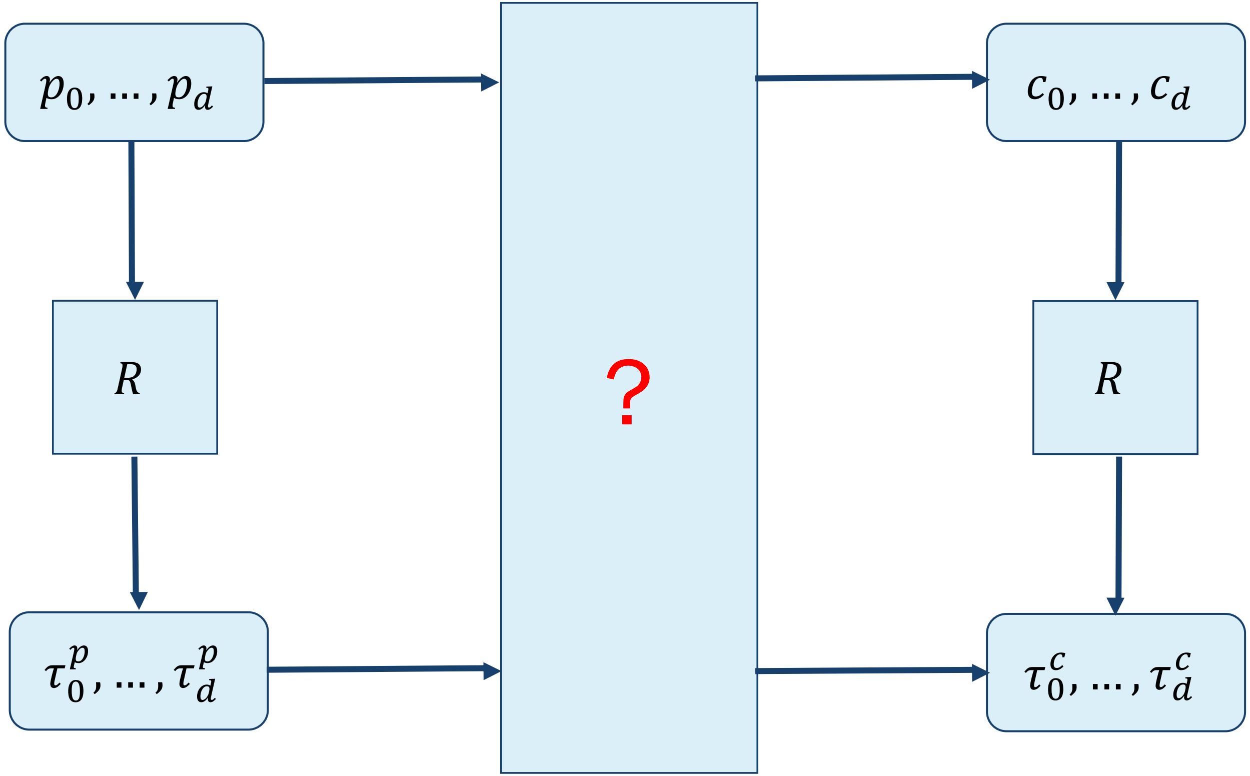
- Against side-channel attacks:
  - *Hiding*
  - ***Masking***



- Against fault attacks:
  - *Repetition, redundancy (error detecting codes), **tags**,...*
  - ***Detection**, correction or **infection***



Combined Attacks



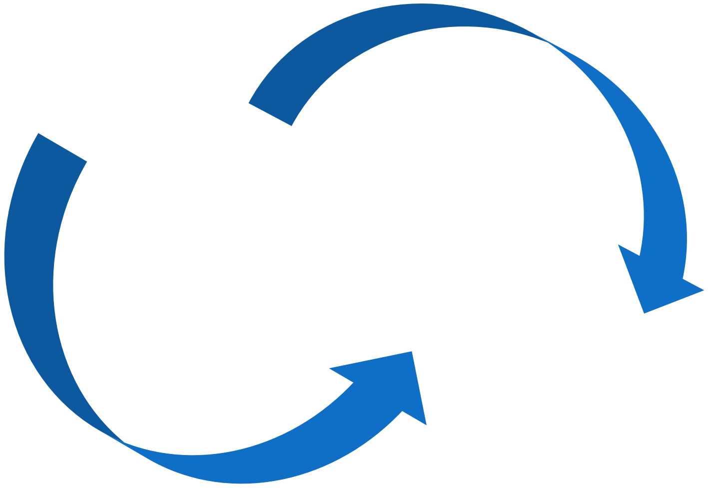
Threshold Cryptography

	MPC	Embedded Systems	
Passive	Shamir's Secret Sharing [1]	Masking TI [3], ...	SCA
Active	SPDZ [2], ...	....	SCA+FA

[1] Adi Shamir: How to Share a Secret. Commun. ACM 22(11): 612-613 (1979)
[2] Ivan Damgård, Valerio Pastro, Nigel P. Smart, Sarah Zakarias: Multiparty Computation from Somewhat Homomorphic Encryption. CRYPTO 2012: 643-662
[3] Svetla Nikova, Vincent Rijmen, Martin Schläffer: Secure Hardware Implementation of Nonlinear Functions in the Presence of Glitches. J. Cryptology 24(2): 292-321 (2011)

Two Proposals:

- M&M:
  - To be presented at CHES 2019 [2]
  - Extension of Masking schemes (TI,...)

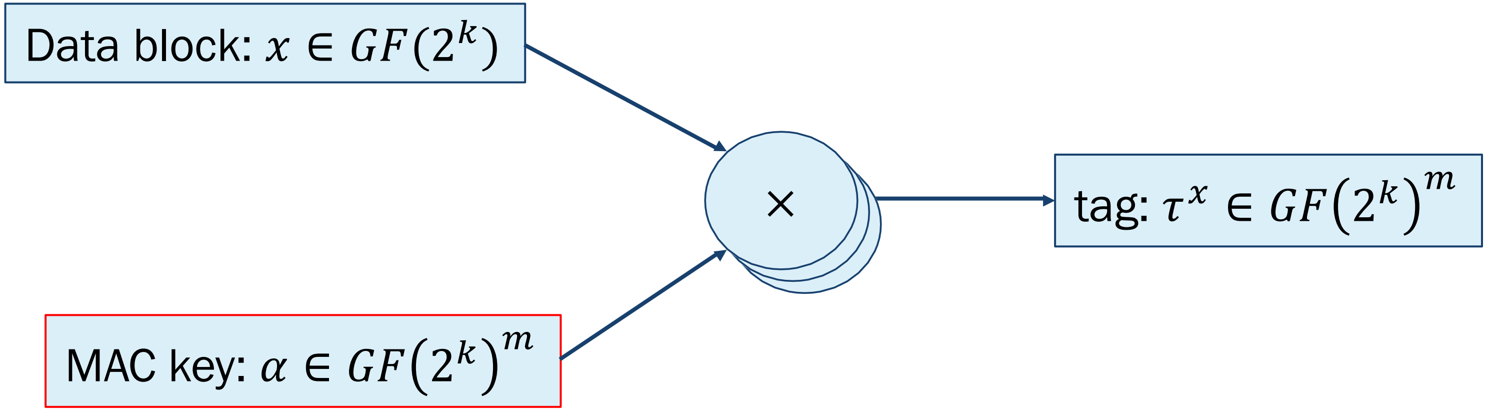


- CAPA:
  - Presented at Crypto 2018 [1]
  - Based on active MPC protocol SPDZ

[1] Oscar Reparaz, Lauren De Meyer, Begül Bilgin, Victor Arribas, Svetla Nikova, Ventzislav Nikov, Nigel P. Smart: CAPA: The Spirit of Beaver Against Physical Attacks. CRYPTO (1) 2018: 121-151

[2] Lauren De Meyer, Victor Arribas, Svetla Nikova, Ventzislav Nikov, Vincent Rijmen: M&M: Masks and Macs against Physical Attacks. IACR Trans. Cryptogr. Hardw. Embed. Syst.2019(1): 25-50 (2019)

Information-theoretic MAC tags

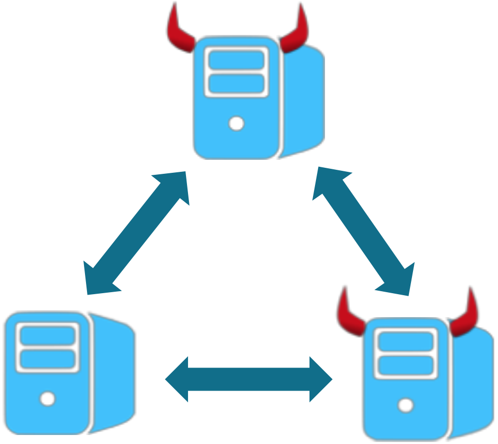


Used 1x!

Secret!

$\Pr[\text{faulted tag=consistent}] = 2^{-km}$

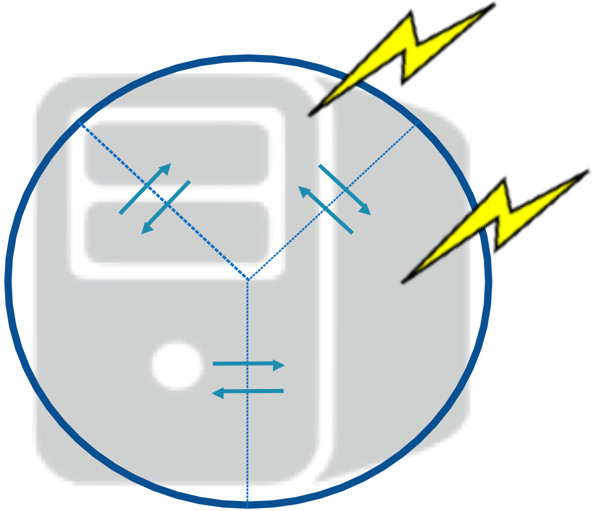
CAPA: from MPC to Embedded Security



- Expensive communication
- Local memory relatively cheap
- Adversaries ⊂ Parties (internal)
- Rushing adversary

- Active Adversary
- Dishonest Majority

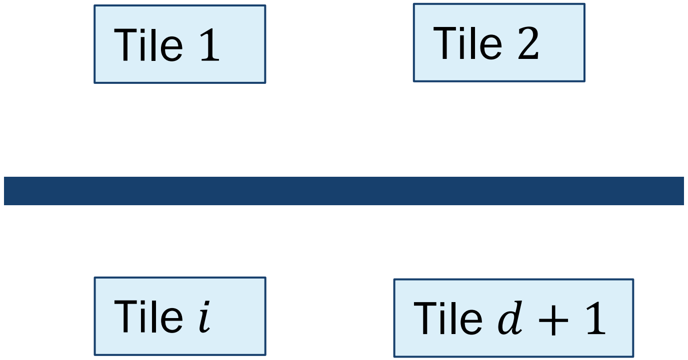
Tile-probe-and-fault-model



- Communication = wiring
- Restricted Storage
- External Adversary
- Zero propagation delay ~ synchronized parties

Tile-probe-and-fault Model

- Static Adversary
- Side-Channel Adversary:
  - *Probe ALL intermediates within d tiles*
  - *Correct value disclosed with probability 1*
- Faulting Adversary:
  - *Exact and known (~very precise laser)*
    - In up to d tiles
    - Probability 1
  - *Random (~clock glitching)*
    - No tile restriction
- Combined Adversary:
  - *Combination and interaction of faults and probes within d tiles*



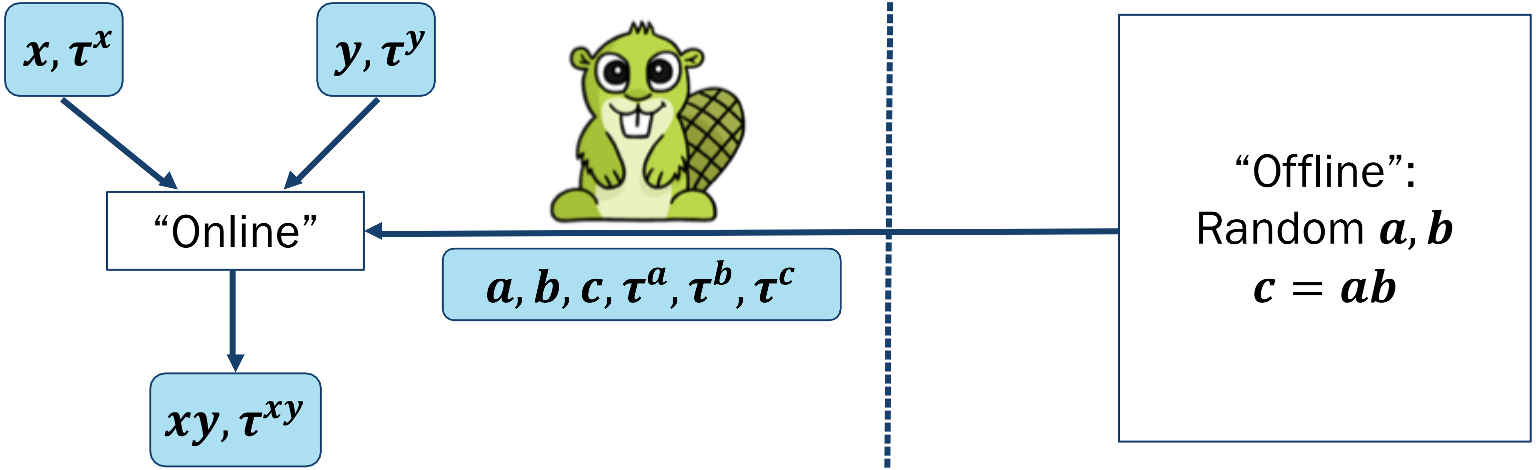
CAPA: Beaver Multiplications

"Online" phase:

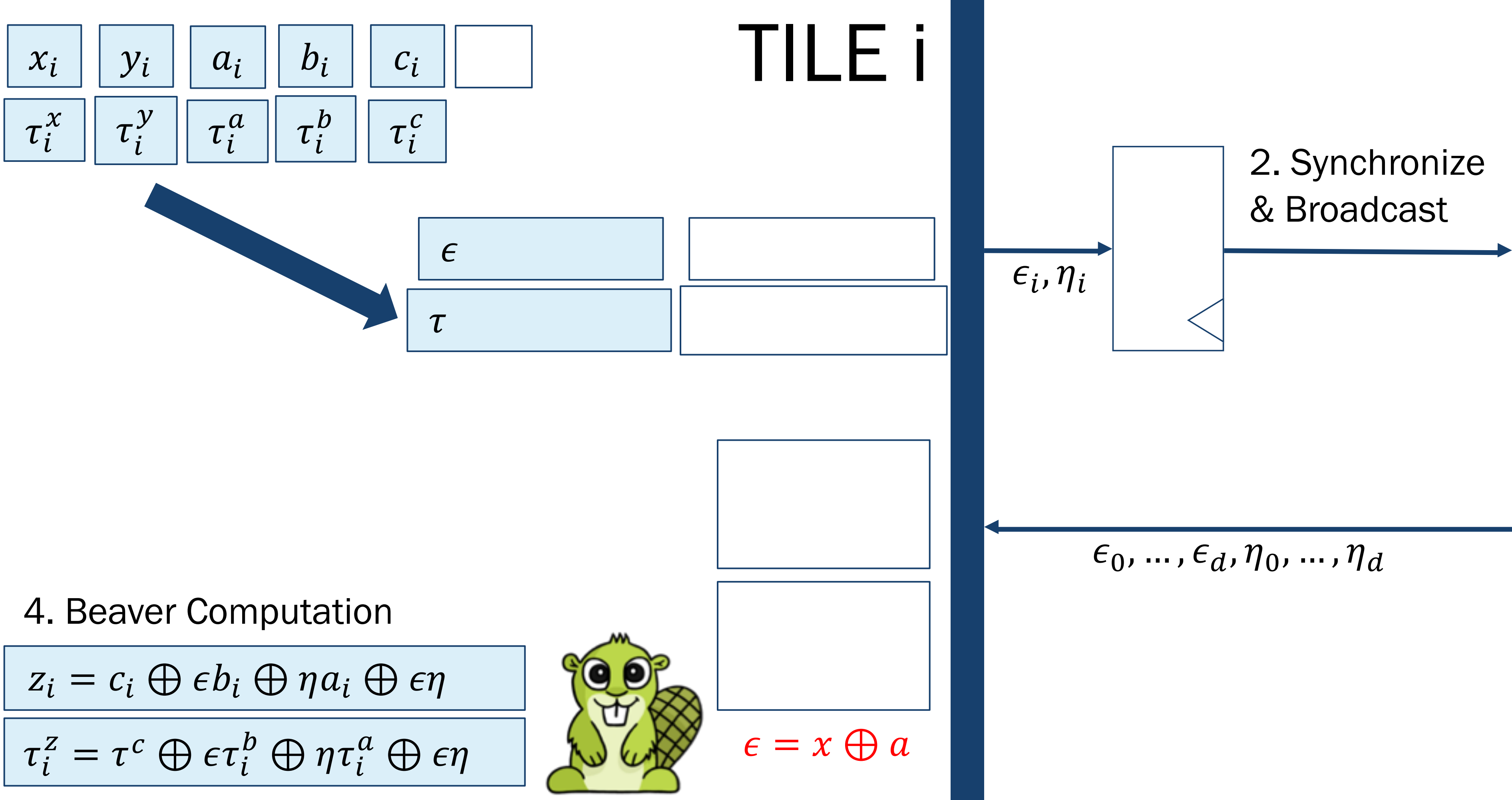
- Beaver multiplications: "Blind" the inputs
- MAC tag check of "Blinded" values

"Offline" phase:

- Generate auxiliary data
- Independent of key/inputs



Donald Beaver: Precomputing Oblivious Transfer. CRYPTO 1995: 97-109


TILE i
x_i y_i a_i b_i c_i
τ_i^x τ_i^y τ_i^a τ_i^b τ_i^c
ϵ
τ
2. Synchronize & Broadcast
ϵ_i, η_i
$\epsilon_0, \ldots, \epsilon_d, \eta_0, \ldots, \eta_d$
4. Beaver Computation
$z_i = c_i \oplus \epsilon b_i \oplus \eta a_i \oplus \epsilon\eta$
$\tau_i^z = \tau^c \oplus \epsilon\tau_i^b \oplus \eta\tau_i^a \oplus \epsilon\eta$
$\epsilon = x \oplus a$

TILE i

x_i | y_i | a_i | b_i | c_i

τ_i^x | τ_i^y | τ_i^a | τ_i^b | τ_i^c

ϵ

τ

2. Synchronize & Broadcast

ϵ_i, η_i

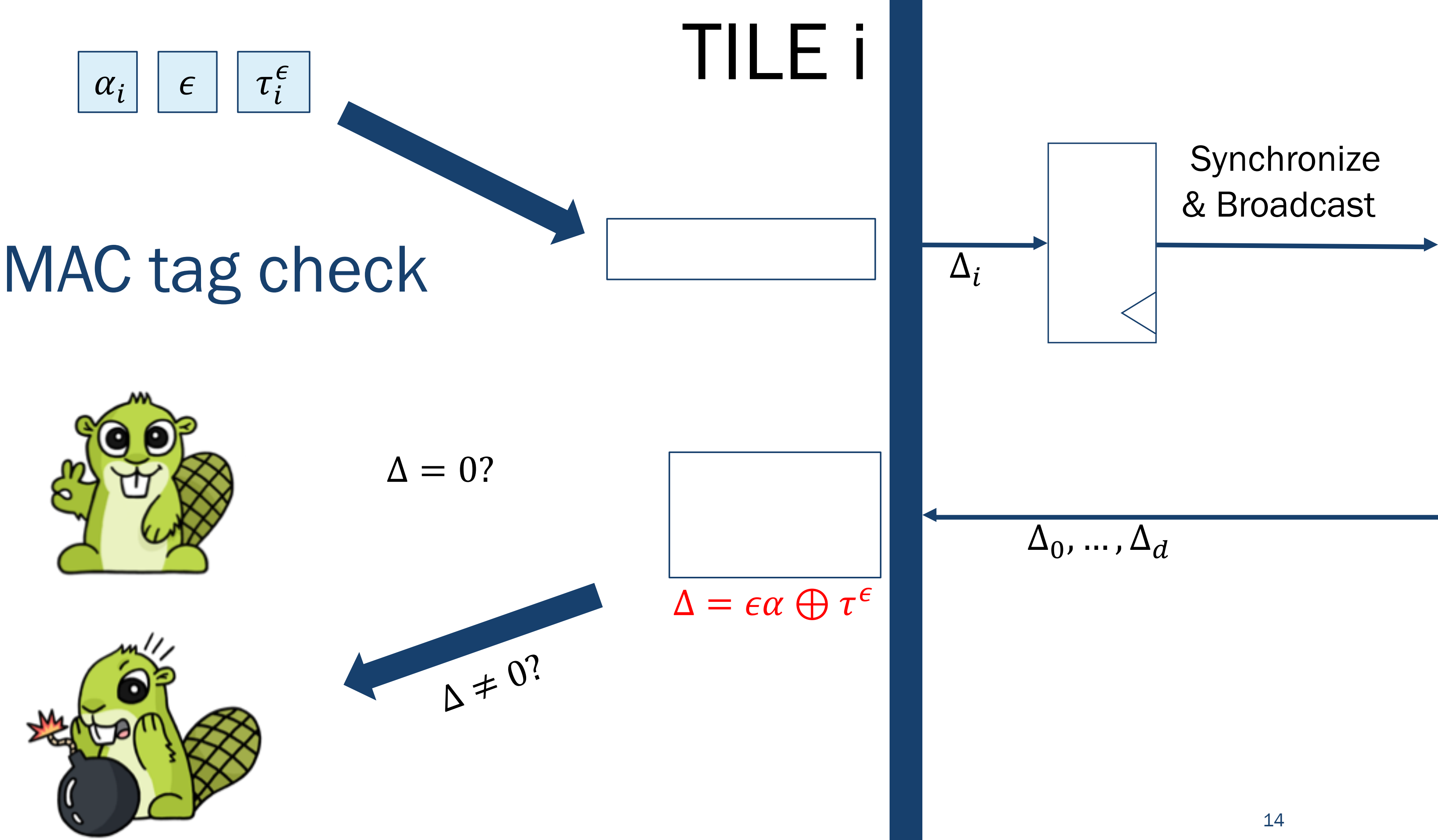
$\epsilon_0, \dots, \epsilon_d, \eta_0, \dots, \eta_d$

4. Beaver Computation

$$z_i = c_i \oplus \epsilon b_i \oplus \eta a_i \oplus \epsilon\eta$$

$$\tau_i^z = \tau^c \oplus \epsilon\tau_i^b \oplus \eta\tau_i^a \oplus \epsilon\eta$$

$\epsilon = x \oplus a$

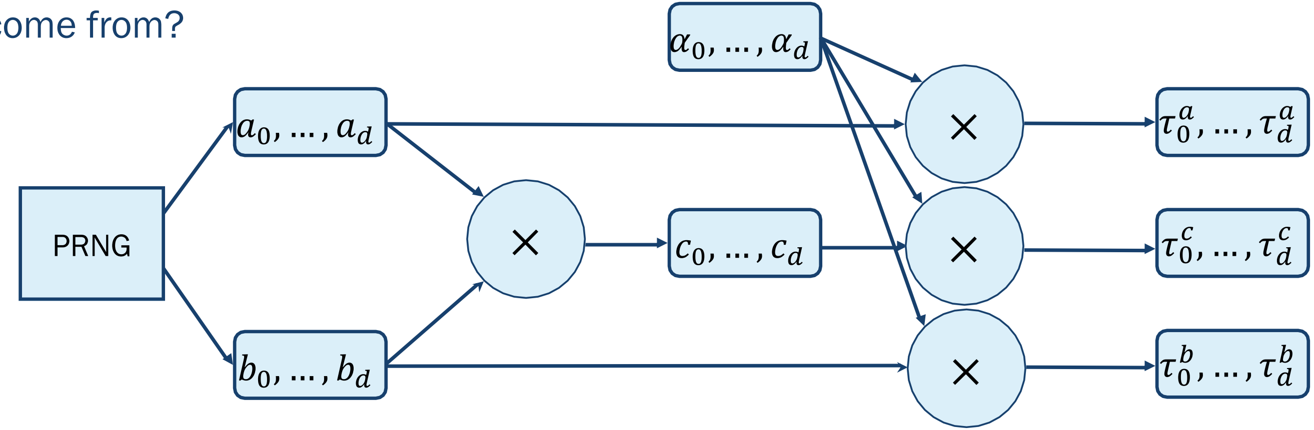

TILE i
MAC tag check
α_i
ϵ
τ_i^ϵ
Δ_i
Synchronize & Broadcast
$\Delta_0, \ldots, \Delta_d$
$\Delta = 0?$
$\Delta = \epsilon\alpha \oplus \tau^\epsilon$
$\Delta \neq 0?$

CAPA Preprocessing Phase

- Where do Beavers come from?

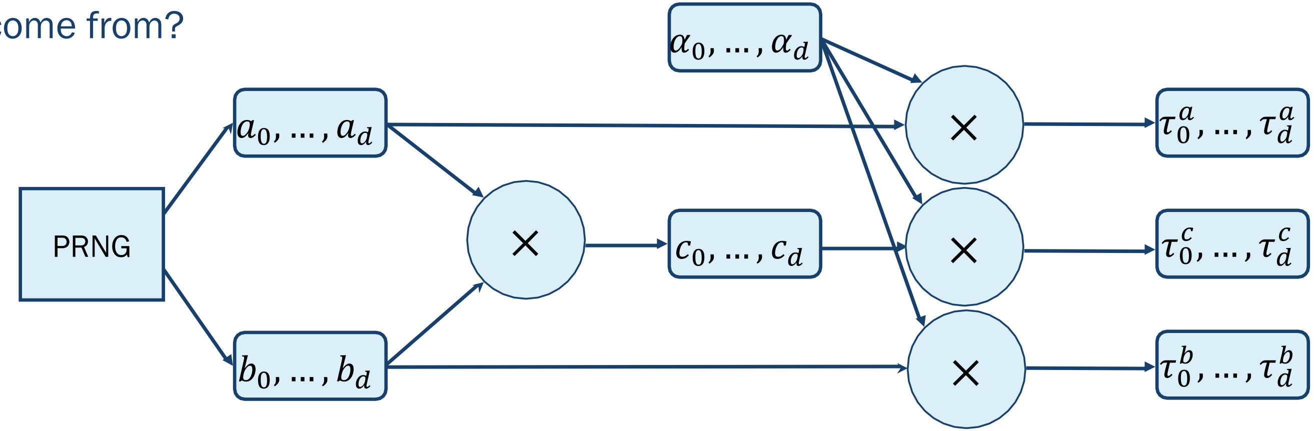
CAPA Preprocessing Phase

- Where do Beavers come from?



CAPA Preprocessing Phase

- Where do Beavers come from?



- Detecting bad Beavers

Like SPDZ: Sacrificing

CAPA Results

- Implementation = very costly!
  - *Example: AES with detection probability 0.996*

	$d = 1$	$d = 2$
Area (kGE)	**122**	**215**
- Evaluation	28	42
- Preprocessing	94	173
Randomness/S-box (bytes)	64	156

- *Superstrong* security:
  - *Adversary is **very** powerful*
  - *~internal adversary (MPC)*
  - *realistic?*

- The alternative route to combined countermeasures:
  - *Start from masking*
  - *Add fault countermeasure*

M&M Adversary Model

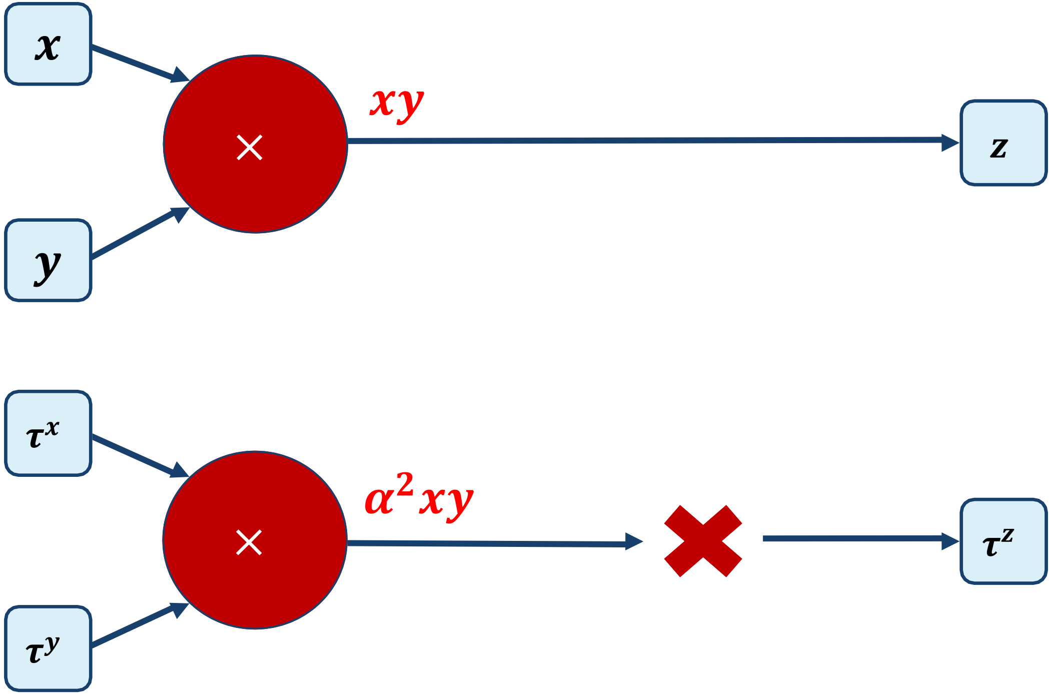
- Side-Channel Adversary:
  - *d-probing model*
  - *Noisy leakage model*
- Faulting Adversary:
  - *Fault = stochastic additive error*
    - Unlimited # bits
  - *Fault = exact*
    - Limited to d shares
- NOT tile-probe-and-fault

M&M Multiplication

TI
DOM
CMS
...

Masks:

MACs:

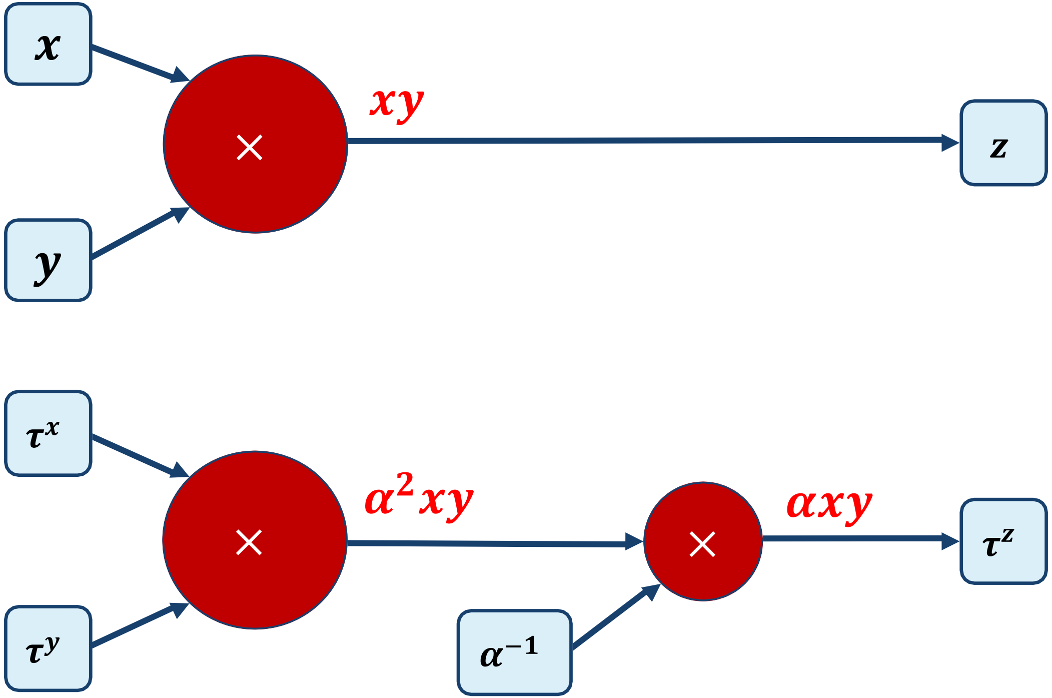


M&M Multiplication

TI
DOM
CMS
...

Masks:

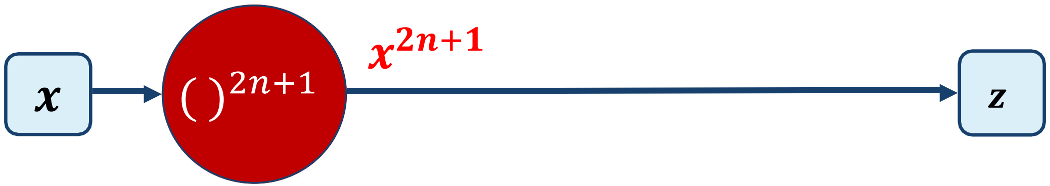
MACs:



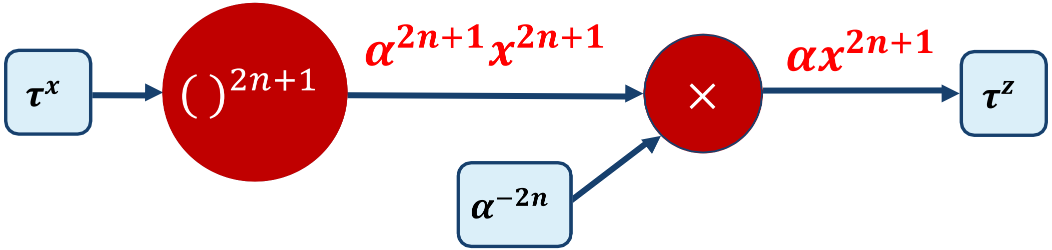
Or other operations....

TI
DOM
CMS
...

Masks:



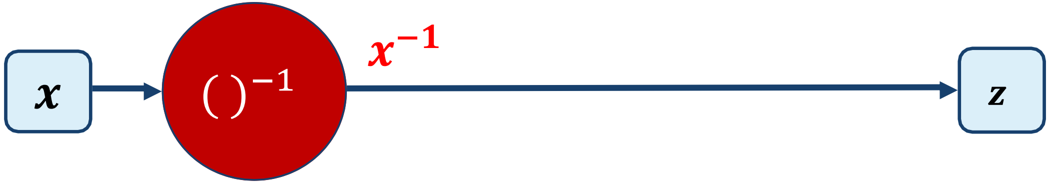
MACs:



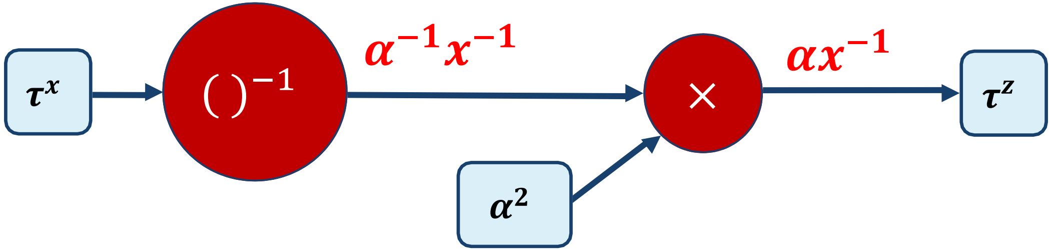
And even...

TI
DOM
CMS
...

Masks:



MACs:

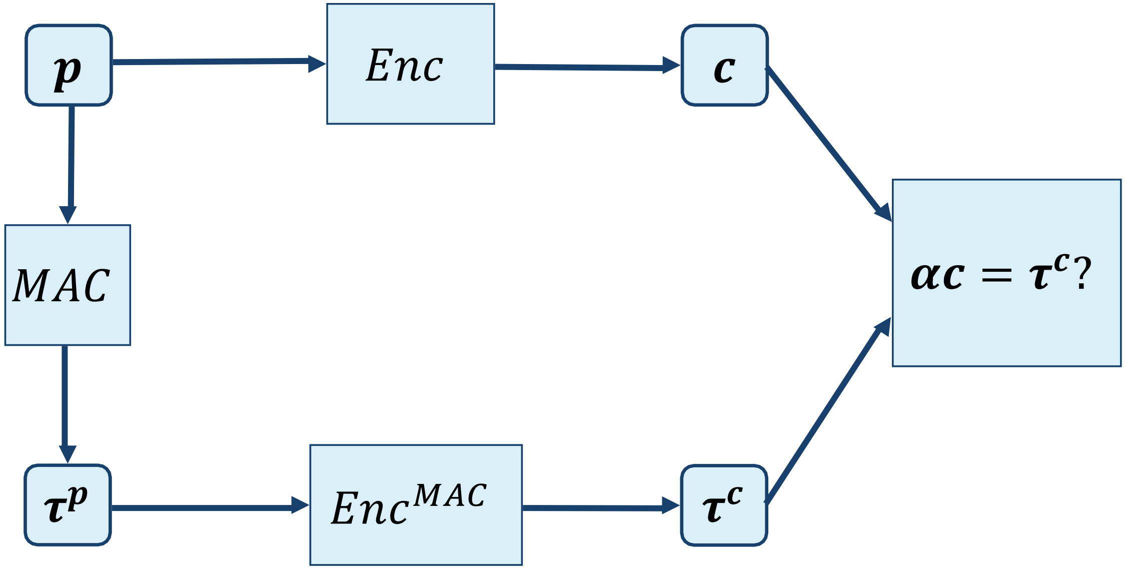


Building blocks for any algorithm

Many flavors of masking

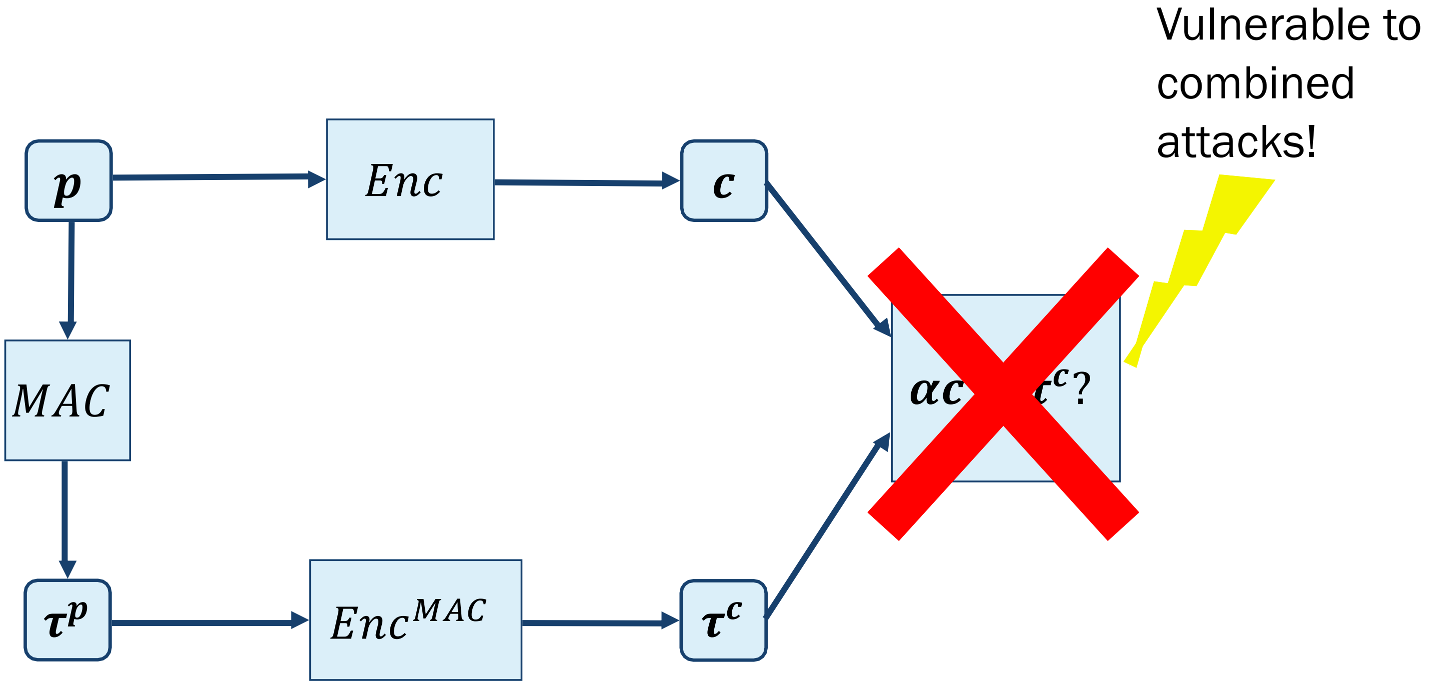
→ many flavors of M&M

How to check?

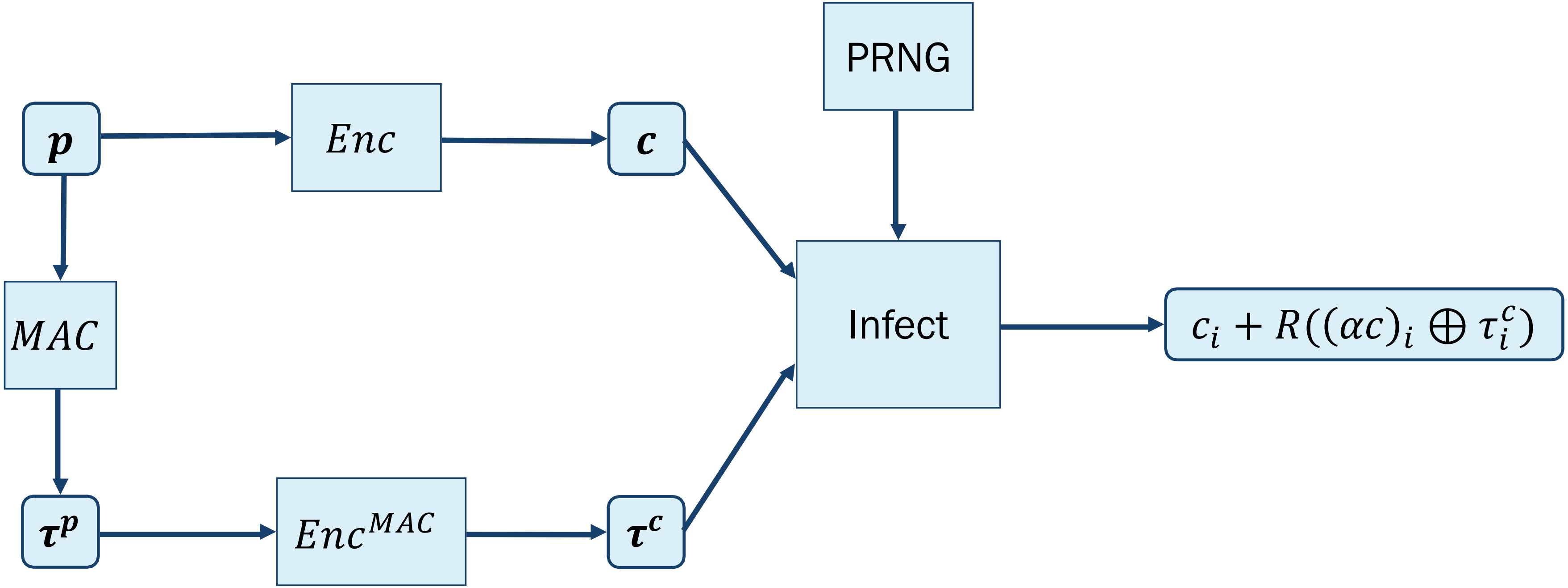


$\boldsymbol{p}$
Enc
$\boldsymbol{c}$
MAC
$\boldsymbol{\alpha c = \tau^c?}$
$\boldsymbol{\tau^p}$
Enc^{MAC}
$\boldsymbol{\tau^c}$

How to check?



Infective Computation



M&M Results

- Much Lower cost
  - *Example: AES with detection probability 0.996*

	$d = 1$	$d = 2$
Area (kGE)	$\mathbf{19.2}$	$\mathbf{33.2}$
Randomness/S-box (bits)	116	348

  - *Overhead factor ~2.53-2.63!*
- Adversary model weaker but more realistic
- BUT combined attacks….
  - *Not vulnerable to state-of-the-art attacks*
  - *But not provably secure since not derived from MPC*

Face-off

d-th order DPA		
- #probes	d	Unlimited in d tiles
- Coupling	✗	✓
- Glitches	✓	✓
d-shot DFA		
- Detection probability	$1-2^{-km}$	$1-2^{-km}$
- Exact faults	Unlimited in d shares	Unlimited in d tiles
- Stochastic faults	Unlimited	Unlimited
- Safe Errors	✗	✓
Combined Attacks		
- Resist PACA [1]	✓	✓
- Provable security	✗	✓

[1] Frédéric Amiel, Karine Villegas, Benoit Feix, Louis Marcel: Passive and Active Combined Attacks: Combining Fault Attacks and Side Channel Analysis. FDTC2007: 92-102

What’s next?

- Cheaper generation of Beaver triplets?
- Relaxing CAPA adversary?
- Provable security against combined attacks at lower cost?
- Verification tools for combined attacks?

QUESTIONS?