The Interpose PUF (iPUF): Secure PUF Design against State-of-the-art Machine Learning based Modeling Attacks

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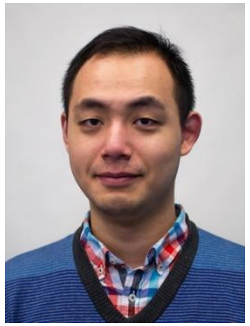
Ha

Durga



Chenglu

Kaleel

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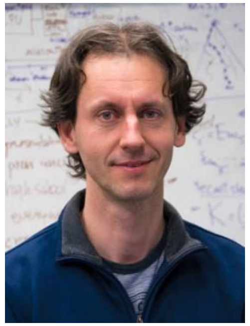

Marten

CHES 2019

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2. Strong PUFs: APUF, XOR APUF and Interpose PUF (iPUF)
3. Short-term Reliability
4. Reliability based modeling attacks on XOR PUF: understanding
5. Interpose PUF – a lightweight PUF which is secure against state-of-the art modeling attacks
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1. Concept - Overview - Motivation

Concept - Overview – Motivation [1]

Challenge C → Hardware Primitive [Device] → Response R

Concept - Overview – Motivation [2]

Challenge C → Hardware Primitive [Device] → Response R

Nature: process variation – physically unclonability - unique

Application: device Identification, authentication and crypto key generation

Concept - Overview – Motivation [3]

Challenge C → Hardware Primitive [Device] → Response R

PUF's Category:

Weak PUF - small #CRPs:
RO PUF, SRAM PUF, etc.

Strong PUF – large #CRPs:

Concept - Overview – Motivation [4]

Challenge C → Hardware Primitive [Device] → Response R

PUF's Category:

- Weak PUF - small #CRPs: RO PUF, SRAM PUF, etc.
- Strong PUF – large #CRPs:

PUF's Modeling Attacks with CRPs only:

- Classical ML attacks – reliable CRPs: Support Vector Machine (SVM), Logistic Regression (LR), Evolution Strategy (ES), Covariance Matrix Adaptation ES (CMA-ES), Perceptron, Boolean Attacks, Deep Neural Network Attacks (DNN)
- Advanced ML attacks – noisy CRPs: CMA-ES + noisy CRPs

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Concept - Overview – Motivation [5]

Challenge C → Hardware Primitive [Device] → Response R

PUF's Category:

- Weak PUF - small #CRPs: RO PUF, SRAM PUF, etc.
- Strong PUF – large #CRPs:
  - **Broken** but **lightweight**: Arbiter PUF/APUF, XOR APUF, Feed Forward PUF, Lightweight Secure PUF, Bistable Ring PUF.
  - **No Security Proof:** Power Grid PUF, Clock PUF, Crossbar PUF
  - **Security Proof:** LPN PUFs - Large HW footprint

PUF's Modeling Attacks with CRPs only:

- **Classical ML attacks** – reliable CRPs: Support Vector Machine (SVM), Logistic Regression (LR), Evolution Strategy (ES), Covariance Matrix Adaptation ES (CMA-ES), Perceptron, Boolean Attacks, Deep Neural Network Attacks (DNN)
- **Advanced ML attacks** – noisy CRPs: CMA-ES + noisy CRPs

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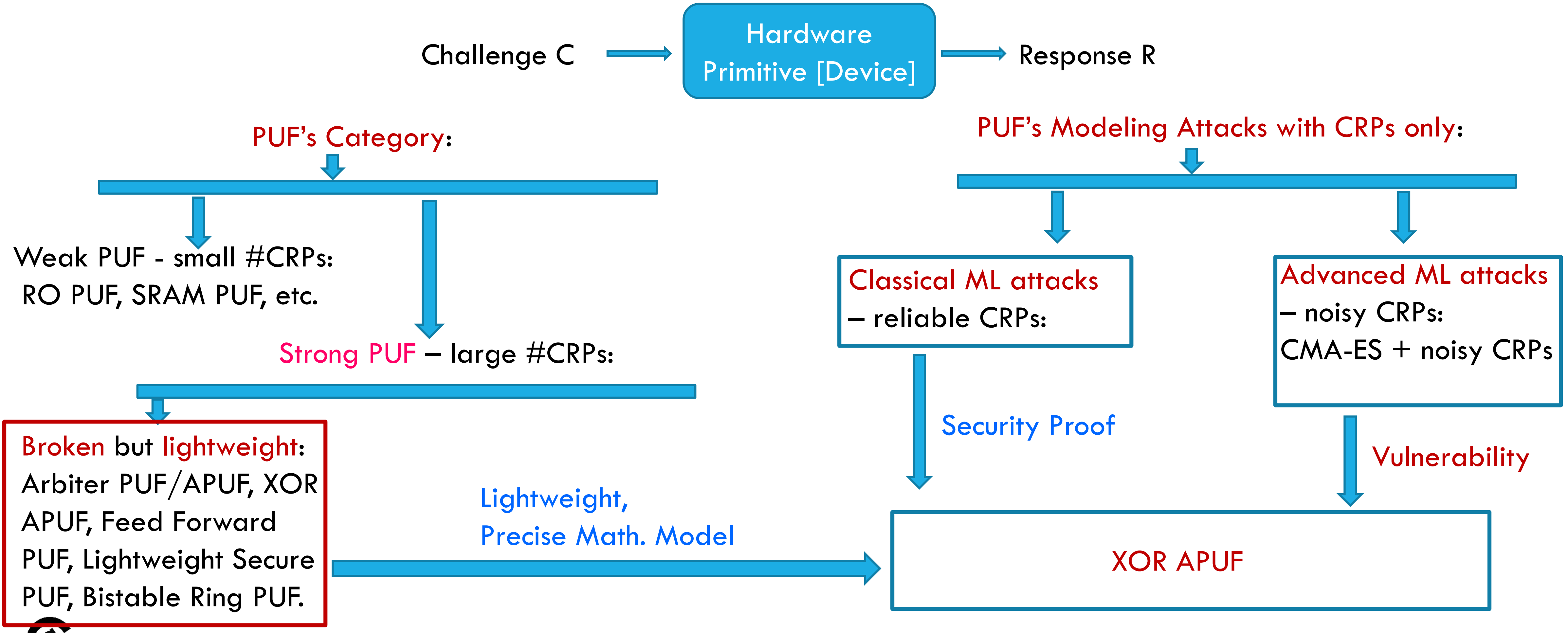
Concept - Overview – Motivation [6]



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Concept - Overview – Motivation [7]

Challenge C → Hardware Primitive [Device] → Response R

PUF's Category:

Weak PUF - small #CRPs:
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Strong PUF – large #CRPs:

Broken but lightweight:
Arbiter PUF/APUF, XOR APUF, Feed Forward PUF, Lightweight Secure PUF, Bistable Ring PUF.

Lightweight,
Precise Math. Model

PUF's Modeling Attacks with CRPs only:

Classical ML attacks
– reliable CRPs:

Security Proof

Advanced ML attacks
– noisy CRPs:
CMA-ES + noisy CRPs

Security Proof

XOR APUF → interpose PUF (iPUF)

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Concept - Overview – Motivation [8]

Challenge C → Hardware Primitive [Device] → Response R

PUF's Category:

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Lightweight,
Precise Math. Model

Design Philosophy

PUF's Modeling Attacks with CRPs only:

Classical ML attacks
– reliable CRPs:

Advanced ML attacks
– noisy CRPs:
CMA-ES + noisy CRPs

Security Proof

Security Philosophy

Security Proof

XOR APUF → interpose PUF (iPUF)

2. APUF- XOR APUF -iPUF

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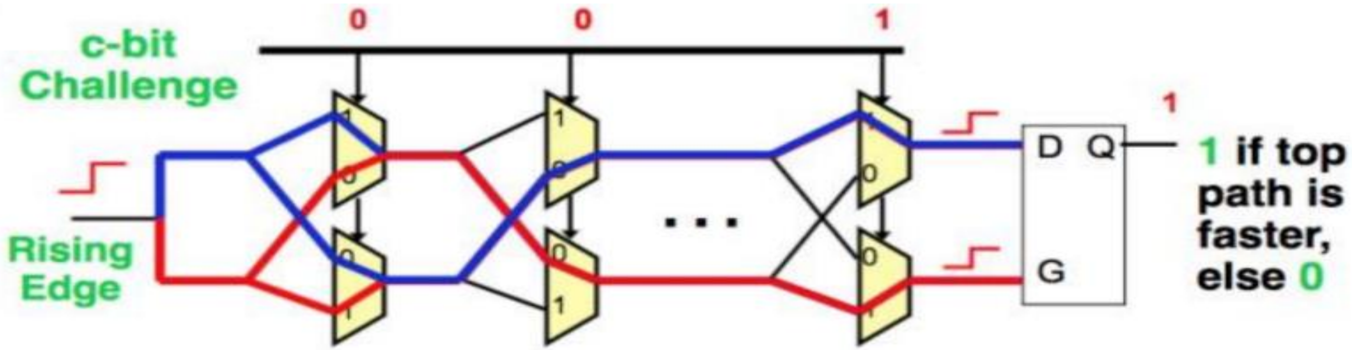
APUF, XOR APUF and iPUF [1]



Arbiter PUF (APUF) [1]

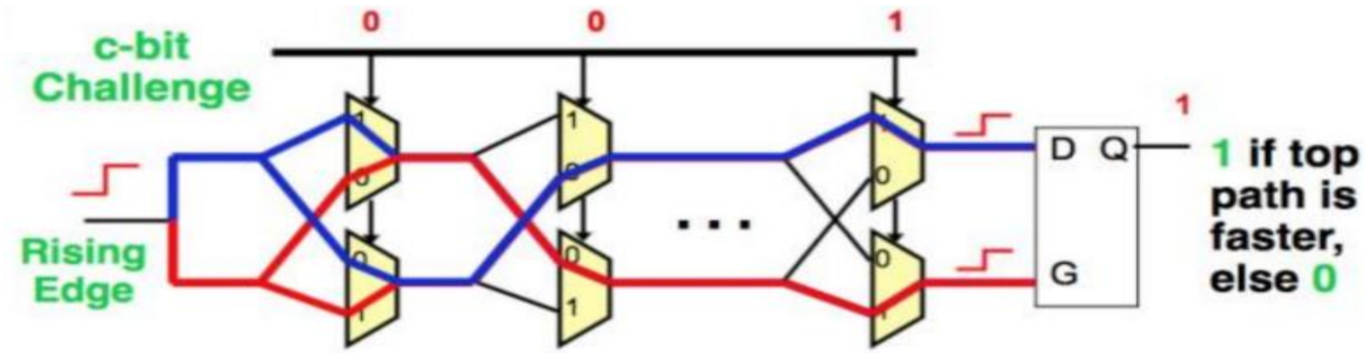
- Extremely lightweight and large number of CRPs i.e, 2^n CRPs

- Environmental noises make the PUF's outputs unreliable sometimes

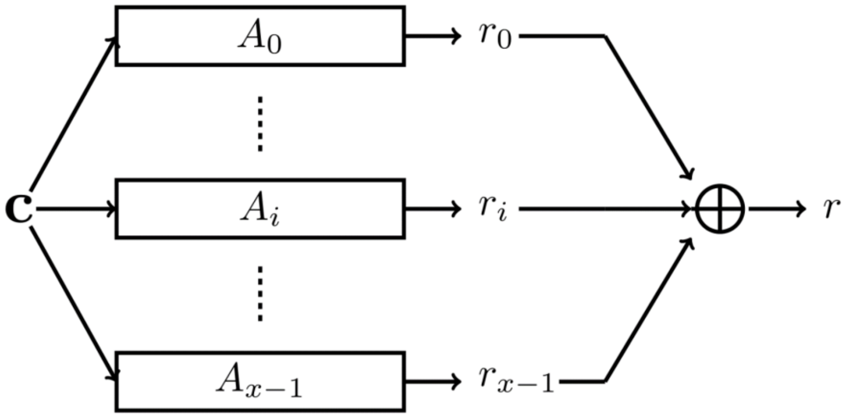
- Not secure against modeling attacks

APUF, XOR APUF and iPUF [2]

Arbiter PUF (APUF)



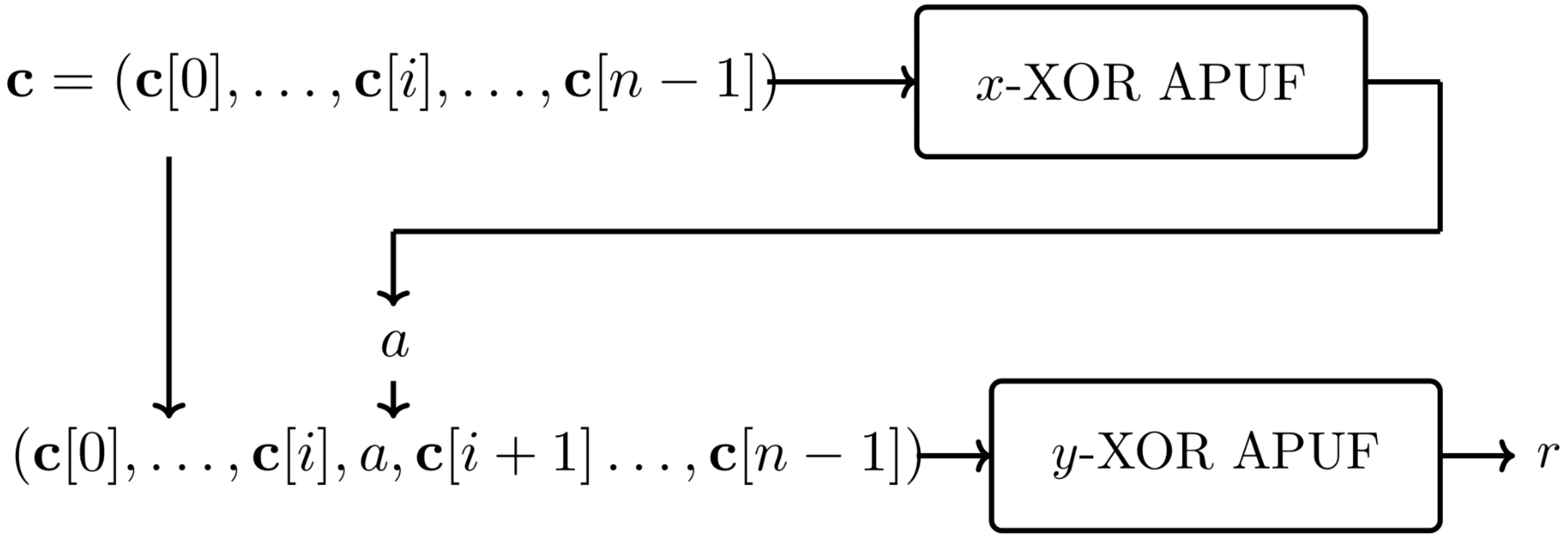
x-XOR APUF



x-XOR PUF.

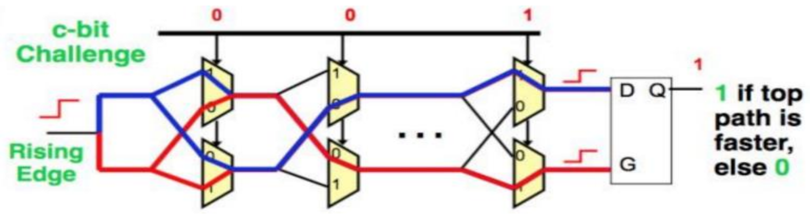
APUF, XOR APUF and iPUF [3]

The Interpose PUF / iPUF

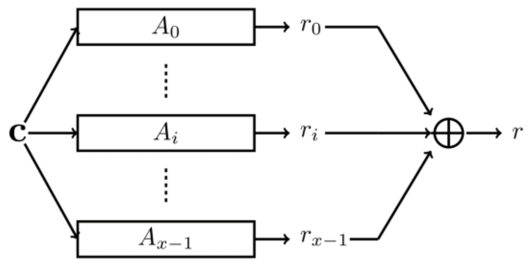


APUF, XOR APUF and iPUF [4]

Arbiter PUF (APUF)

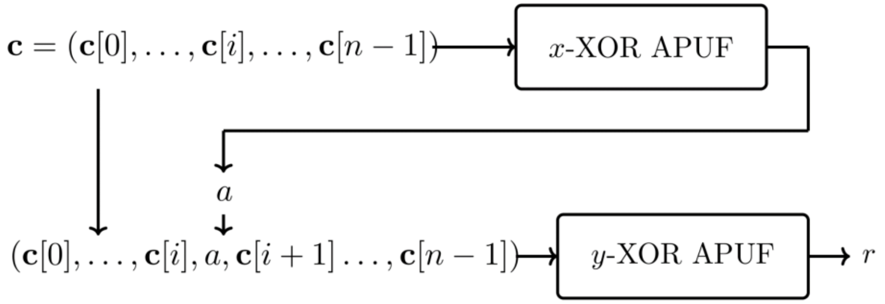


x-XOR Arbiter PUF



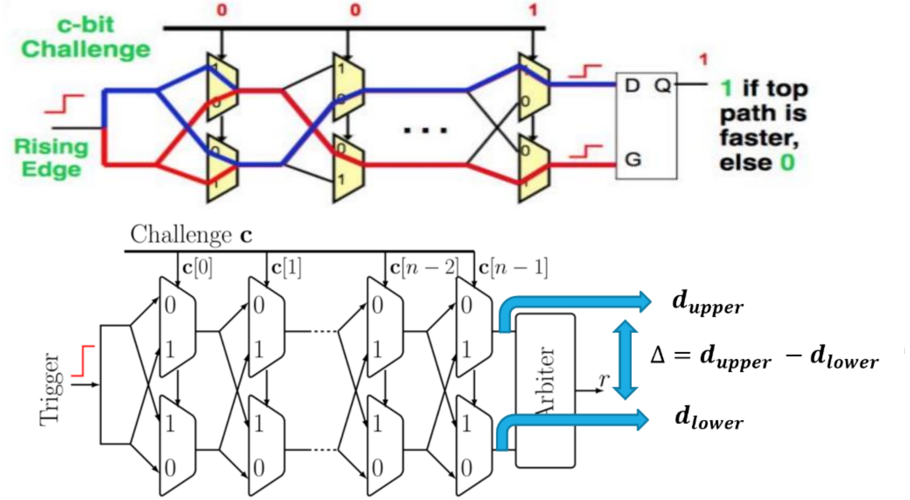
x-XOR PUF.

Interpose PUF (iPUF)



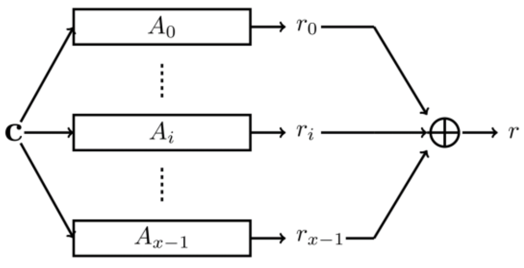
APUF, XOR APUF and iPUF [5]

Arbiter PUF (APUF)



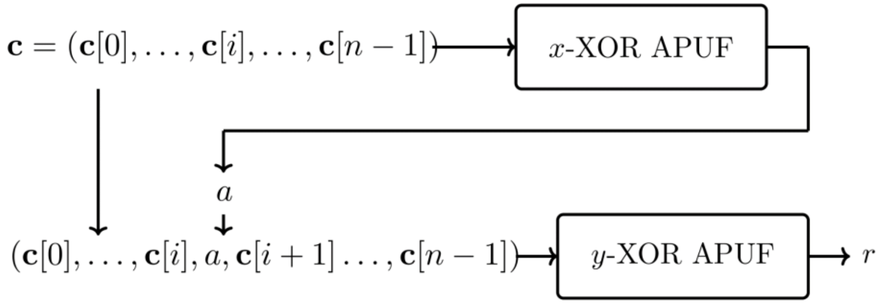
A n-stage classic Arbiter PUF with challenge $\mathbf{c} \in \{0,1\}^n$.

x-XOR Arbiter PUF



x-XOR PUF.

Interpose PUF (iPUF)



- $\Delta > 0 \rightarrow r = 1.\,Otherwise\ r = 0$
- $\Delta = \boldsymbol{d_{upper}} - \boldsymbol{d_{lower}} = \boldsymbol{w} \cdot \boldsymbol{\Phi}$
- $\boldsymbol{w}$: *unique for any APUF instance*
- $\boldsymbol{\Phi}$ *is the parity vector*

$\boldsymbol{\Phi}[i] = \prod_{j=i,\ldots,n-1}(1 - \boldsymbol{c}[j]), i = 0, \ldots, n-1\,,\ \boldsymbol{\Phi}[n] = 1$

- Precise linear model
- Large CRP space
- Vulnerable to ML attacks

APUF, XOR APUF and iPUF [6]

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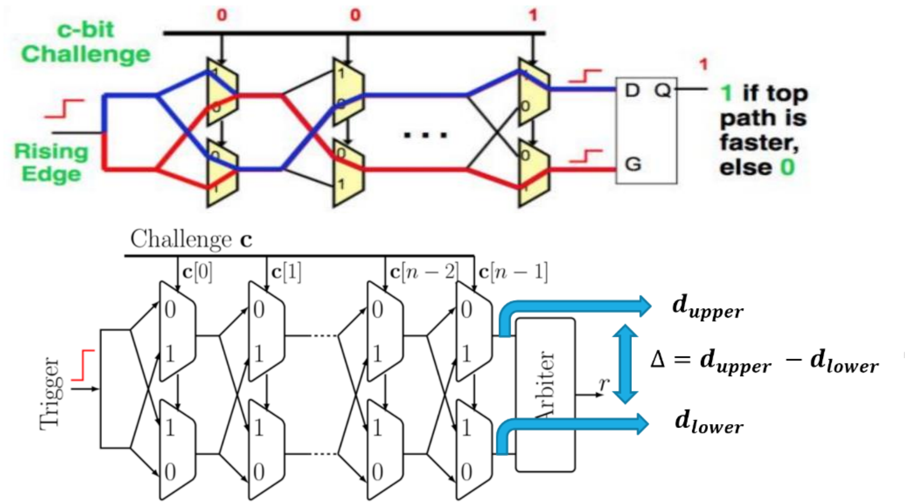
Arbiter PUF (APUF)



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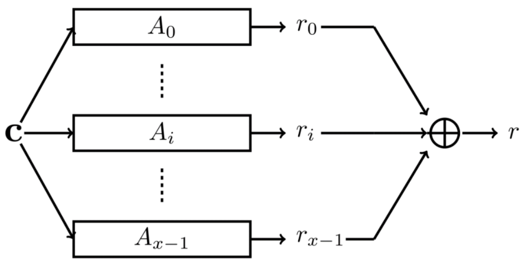
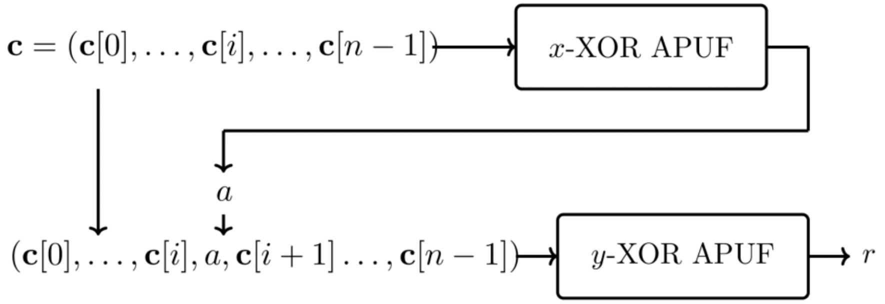
x-XOR Arbiter PUF



x-XOR PUF.

Interpose PUF (iPUF)



$$r_{\text{XOR APUF}} = sign\left(\prod_{i=1}^{x} w_i^{\mathrm{T}} \Phi\right)$$ [2]

- $\Delta > 0 \rightarrow r = 1. Otherwise\ r = 0$
- $\Delta = \boldsymbol{d_{upper}} - \boldsymbol{d_{lower}} = \boldsymbol{w} \cdot \boldsymbol{\Phi}$
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- Precise non-linear model
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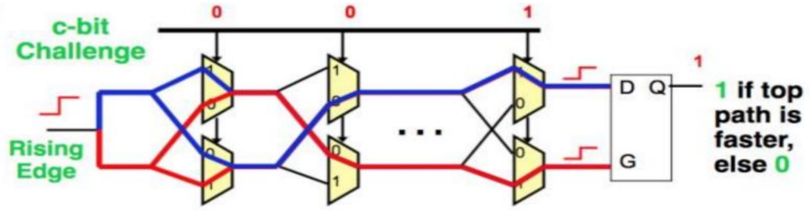
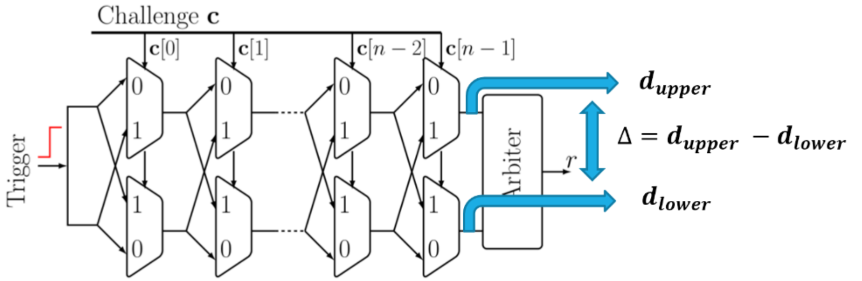
- Secure against classical ML
- Vulnerable to advanced ML

APUF, XOR APUF and iPUF [7]

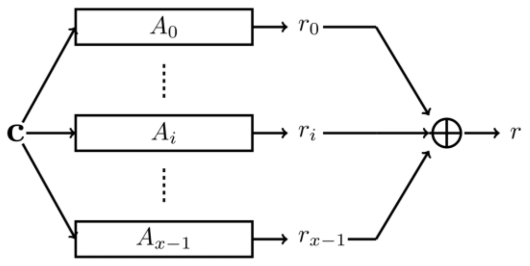
Arbiter PUF (APUF)





A n-stage classic Arbiter PUF with challenge $\mathbf{c} \in \{0,1\}^n$.

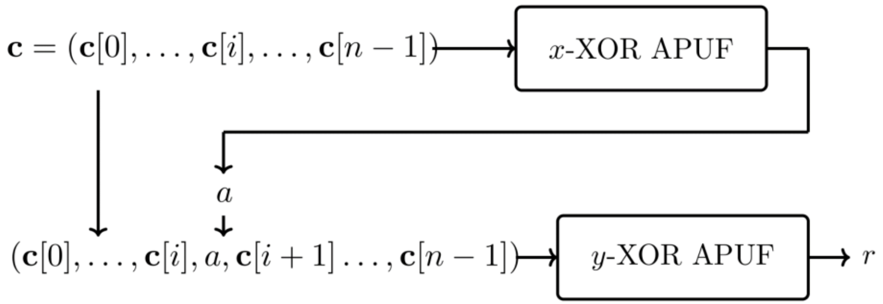
x-XOR Arbiter PUF



x-XOR PUF.

$$r_{\text{XOR APUF}} = sign\left(\prod_{i=1}^{x} w_i^{\mathrm{T}} \Phi\right)$$

Interpose PUF (iPUF)



$$(x, y) - IPUF \approx \left(y + \frac{x}{2}\right) - XOR\ PUF$$

if a is inserted at the middle

- $\Delta > 0 \rightarrow r = 1. Otherwise\ r = 0$
- $\Delta = \boldsymbol{d_{upper}} - \boldsymbol{d_{lower}} = \boldsymbol{w} \cdot \boldsymbol{\Phi}$
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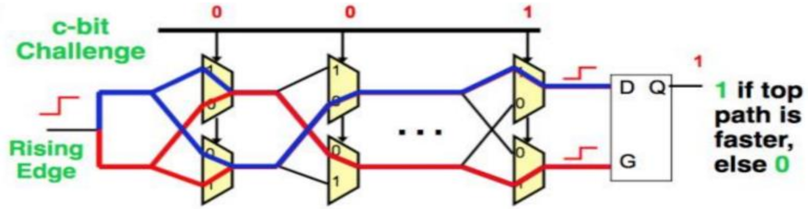
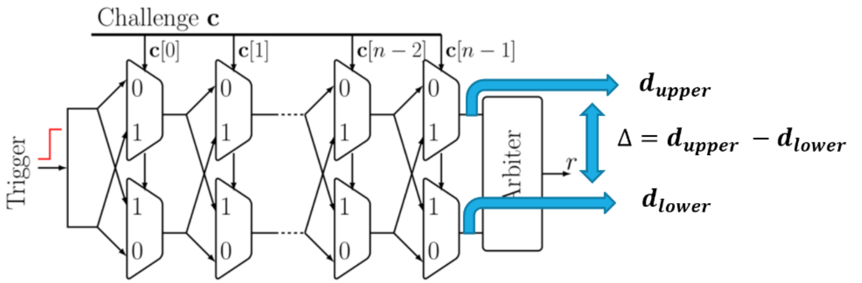
APUF, XOR APUF and iPUF [8]

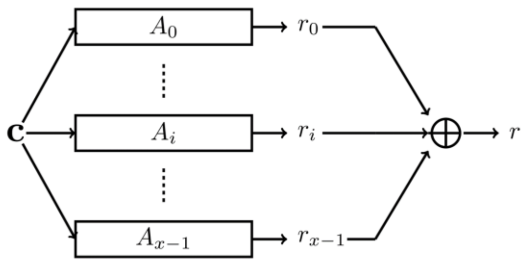
Arbiter PUF (APUF)





A n-stage classic Arbiter PUF with challenge $\mathbf{c} \in \{0,1\}^n$.

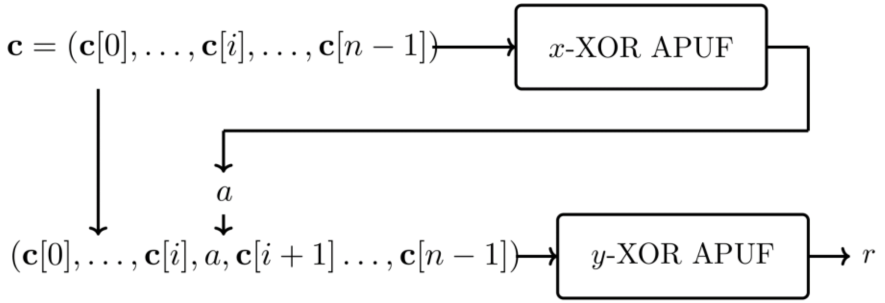
x-XOR Arbiter PUF



x-XOR PUF.

$$r_{\text{XOR APUF}} = sign\left(\prod_{i=1}^{x} w_i^{\mathrm{T}} \Phi\right)$$

Interpose PUF (iPUF)



$$(x, y) - IPUF \approx \left(y + \frac{x}{2}\right) - XOR\ PUF$$

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x-XOR Arbiter PUF:

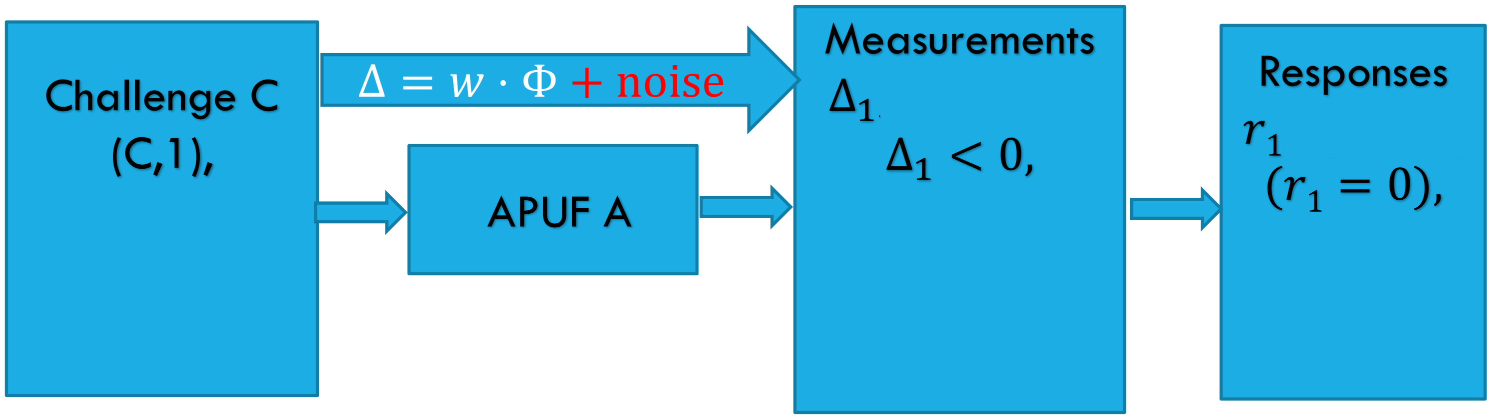
- Precise non-linear model
- Large CRP space
- Secure against classical ML
- Vulnerable to advanced ML

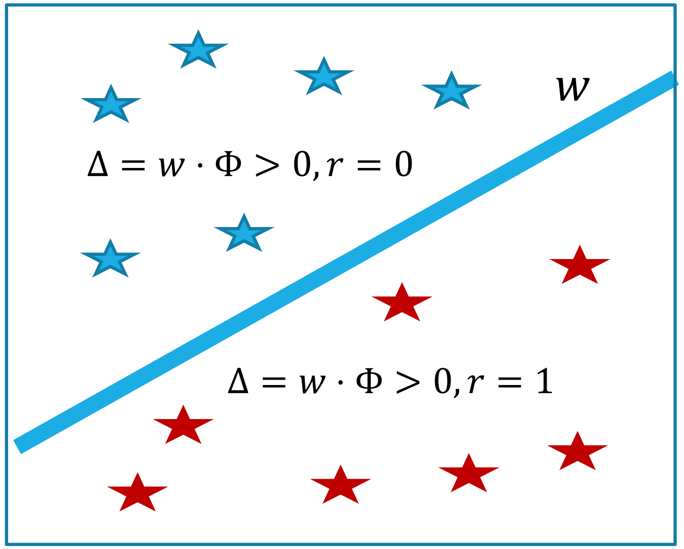
Interpose PUF (iPUF):

- Precise non-linear model
- Large CRP
- **Secure both classical ML and advanced ML**

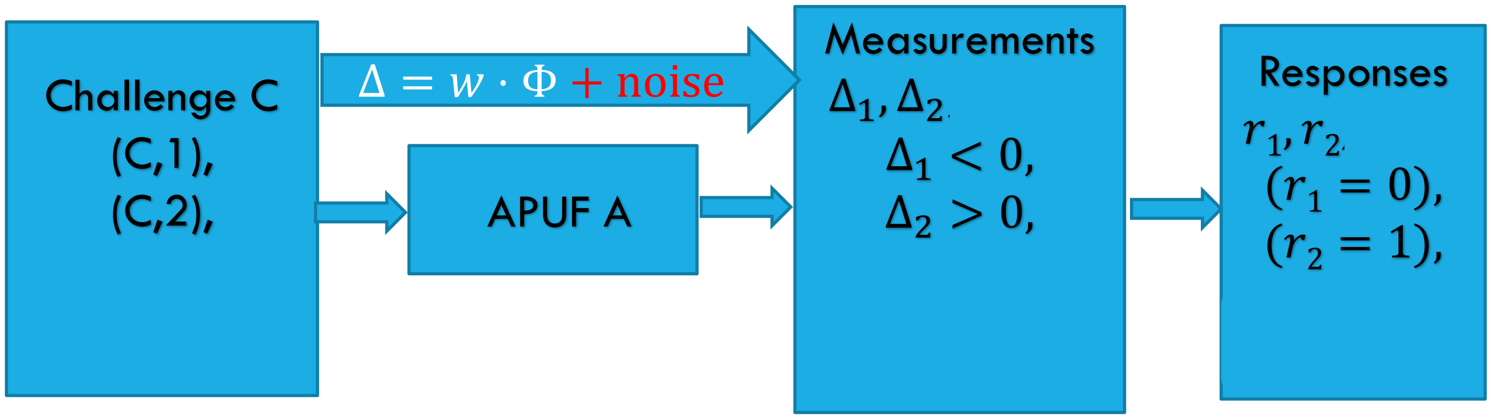
3. Short-term Reliability

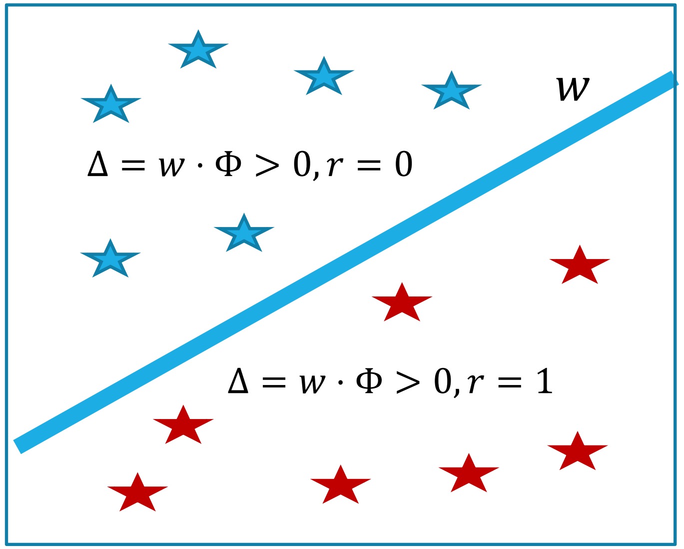
Arbiter: Repeatability – short-term Reliability [1]



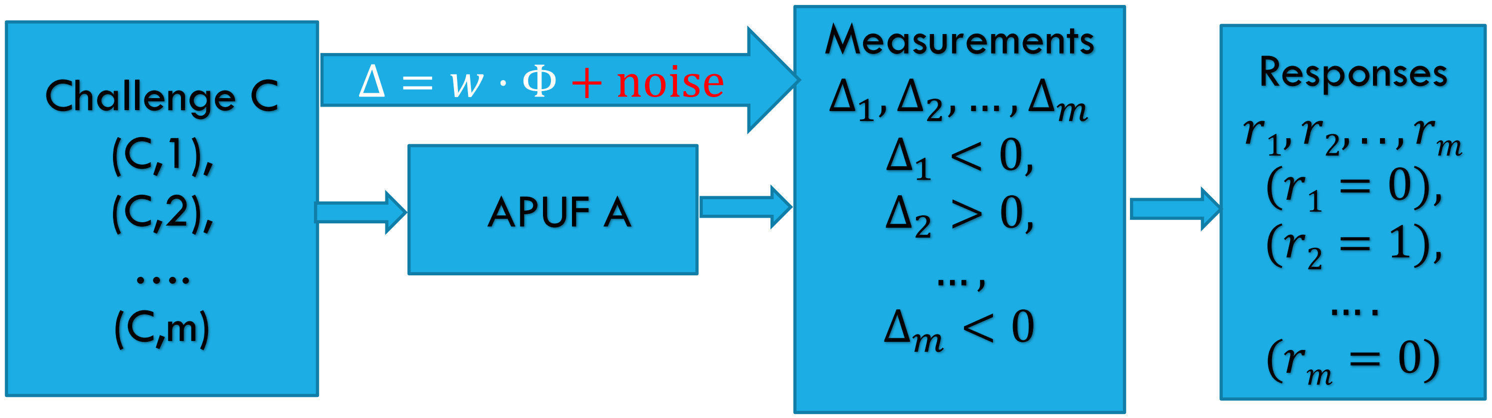


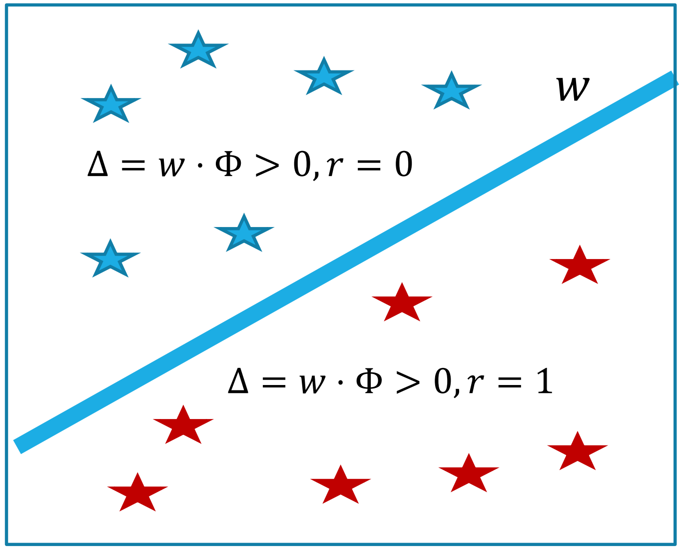
Arbiter: Repeatability – short-term Reliability [2]





Arbiter: Repeatability – short-term Reliability [3]





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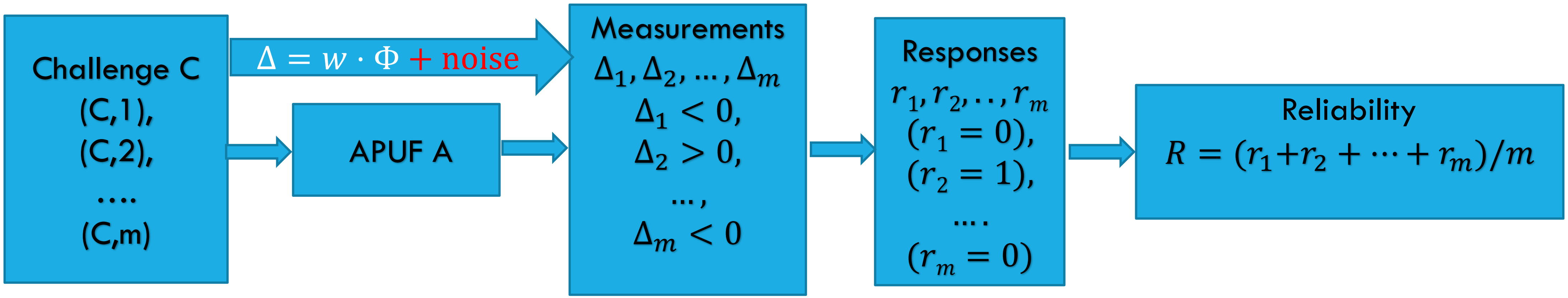
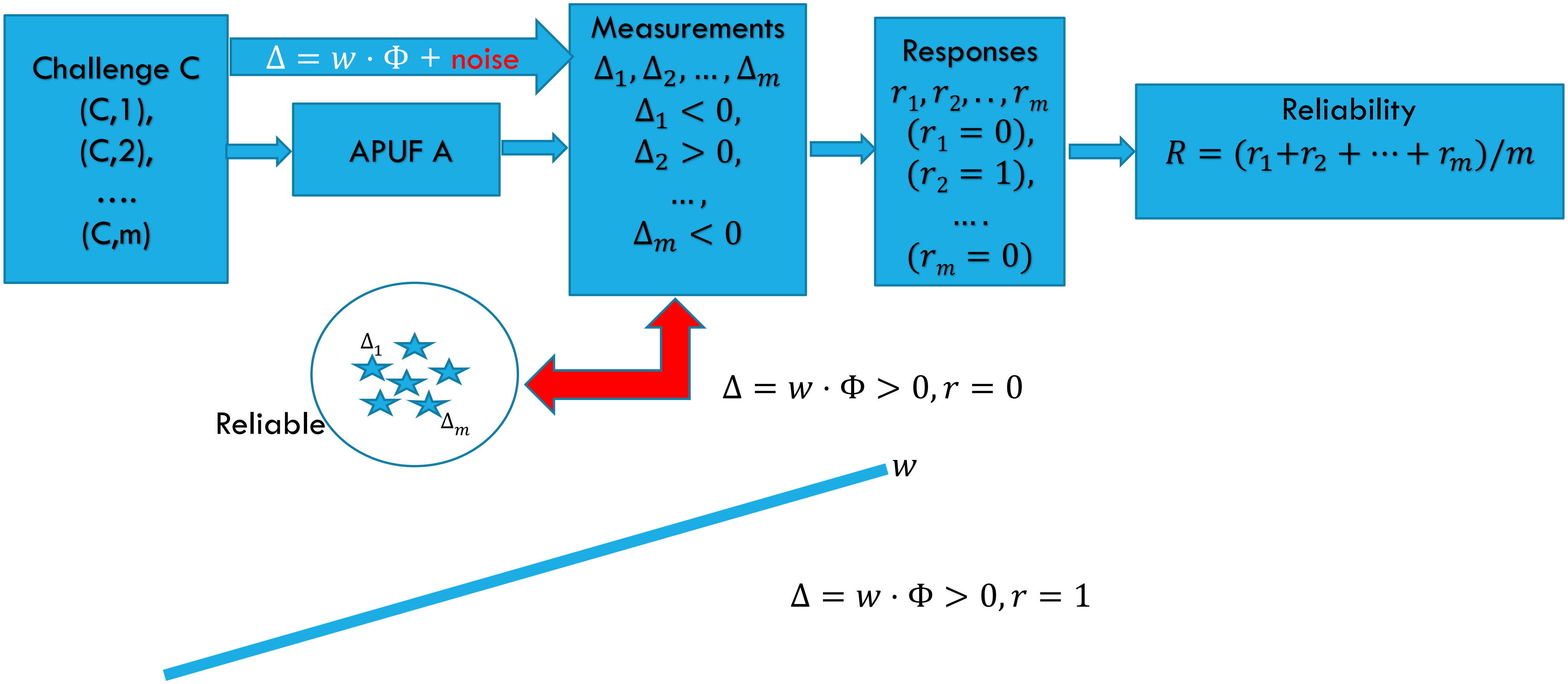
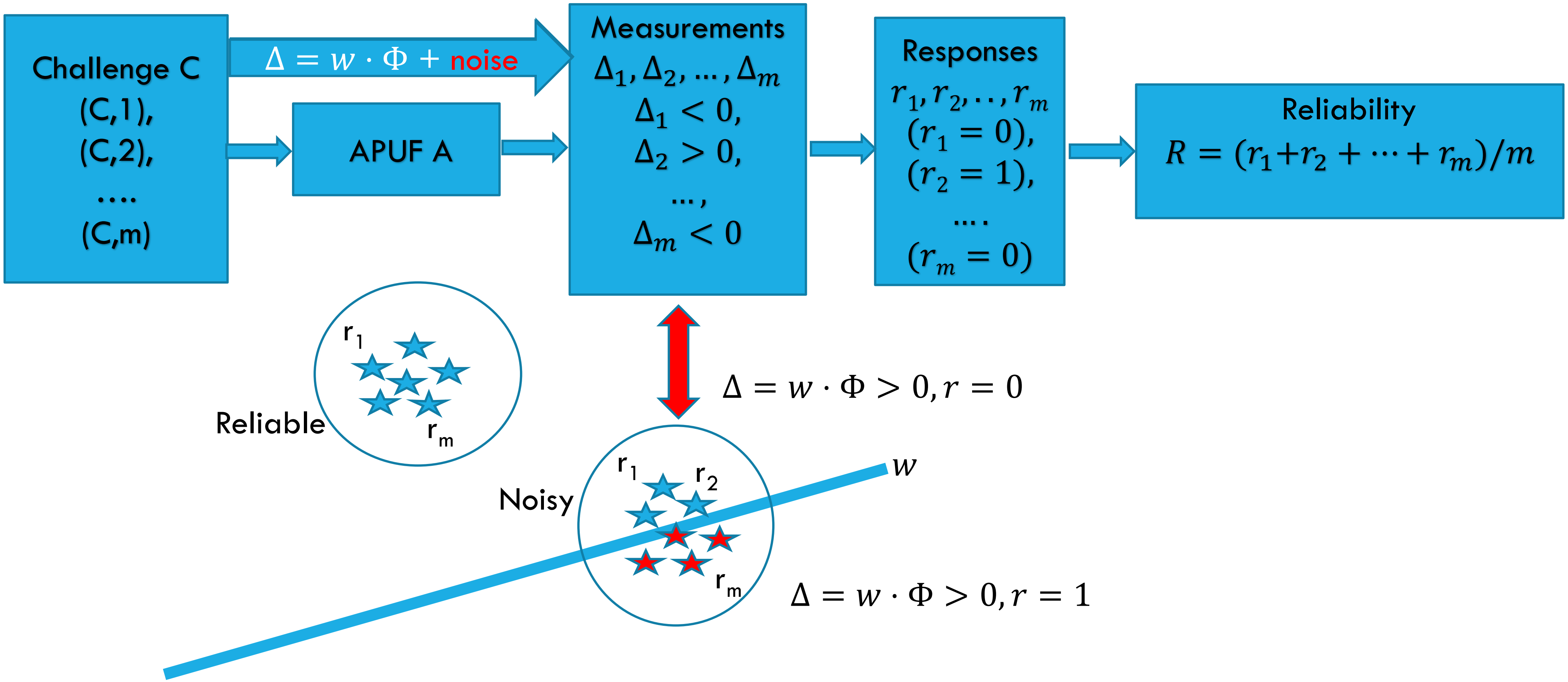
Arbiter: Repeatability – short-term Reliability [4]



Arbiter: Repeatability – short-term Reliability [5]

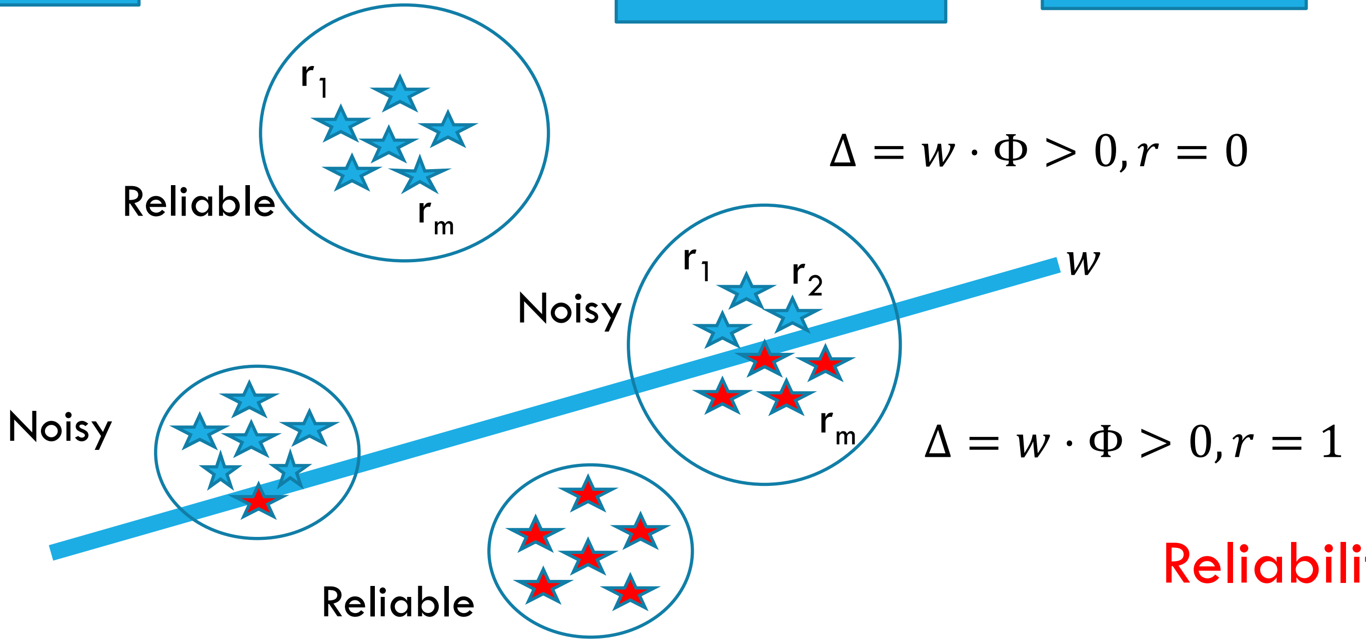


Arbiter: Repeatability – short-term Reliability [6]



Arbiter: Repeatability – short-term Reliability [7]

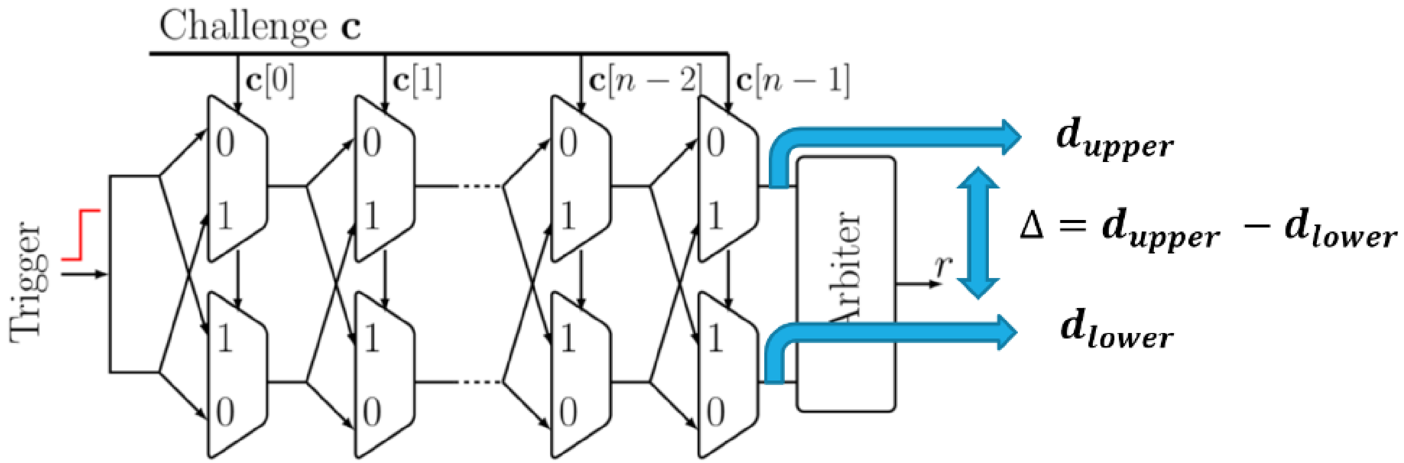
Challenge C		APUF A		Measurements		Responses		Reliability
(C,1), (C,2), …. (C,m)	$\Delta = w \cdot \Phi + \text{noise}$ →		→	$\Delta_1, \Delta_2, \dots, \Delta_m$ $\Delta_1 < 0,$ $\Delta_2 > 0,$ $\dots,$ $\Delta_m < 0$	→	$r_1, r_2, \dots, r_m$ $(r_1 = 0),$ $(r_2 = 1),$ …. $(r_m = 0)$	→	$R = (r_1 + r_2 + \dots + r_m)/m$



Reliability of C and w are related

4. Reliability based Modeling Attacks

APUF



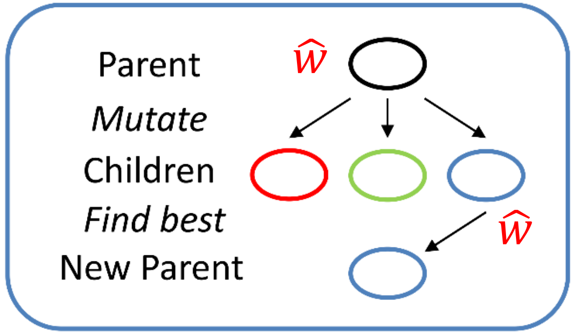
A n-stage classic Arbiter PUF with challenge $\mathbf{c} \in \{0,1\}^n$.

- $\Delta > 0 \rightarrow r = 1. Otherwise\ r = 0$
- $\Delta = \boldsymbol{d_{upper}} - \boldsymbol{d_{lower}} = \boldsymbol{w} \cdot \boldsymbol{\Phi}$

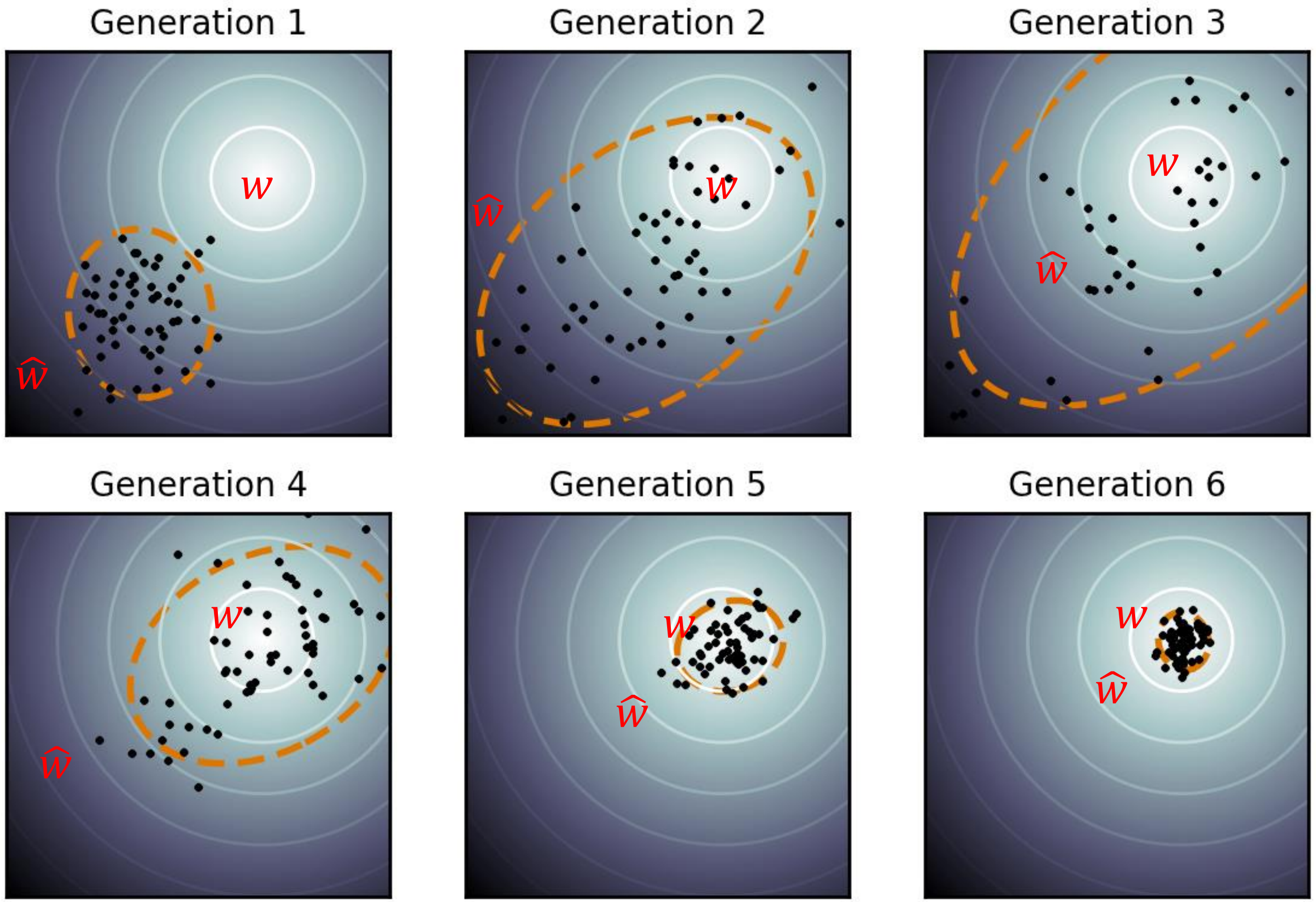
Covariance Matrix Adaptation Evolution Strategy (CMA-ES) Algorithm

$w: target$

$\hat{w}: estimator\ or\ model$



[4] $\hat{w} = w$



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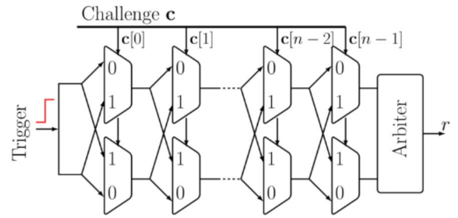
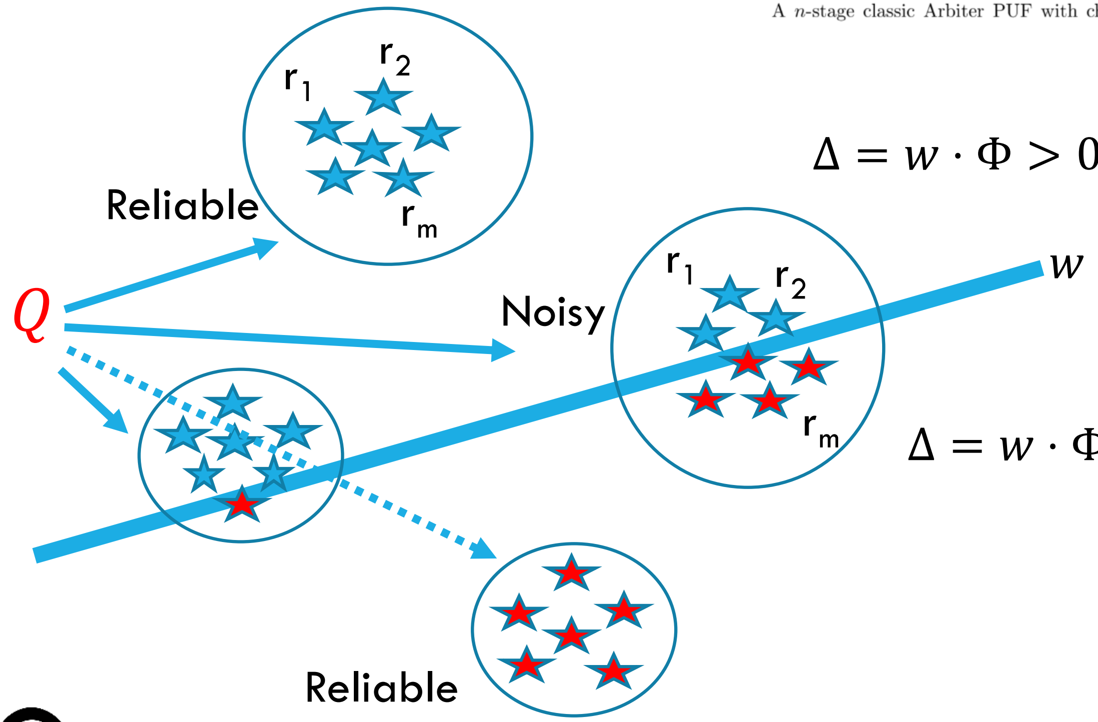
Reliability-based modeling attack on APUFs using CMAES [1]



A n-stage classic Arbiter PUF with challenge $\mathbf{c} \in \{0,1\}^n$.

Q: $set\ of\ CRPs$,
w: $APUF$



$\Delta = w \cdot \Phi > 0, r = 0$

$\Delta = w \cdot \Phi < 0, r = 1$

Q, w

Q_n : noisy challenges

Q_r : reliable challenges

Reliability-based modeling attack on APUFs using CMAES [2]

Iteration 1

Target

Q, w

Q_n : noisy

Q_r : reliable

Model

$Q, \epsilon_1, \hat{w}_1$

$$Q \rightarrow challenge\ c \rightarrow \Phi(c) \rightarrow \ \Delta = \hat{w}_1 \cdot \Phi(c)$$

$$|\Delta| \leq \epsilon_1 \rightarrow \ \ challenge\ c\ is\ noisy$$ → Q_n : noisy

$$|\Delta| > \epsilon_1 \rightarrow \ \ challenge\ c\ is\ reliable$$ → Q_r : reliable

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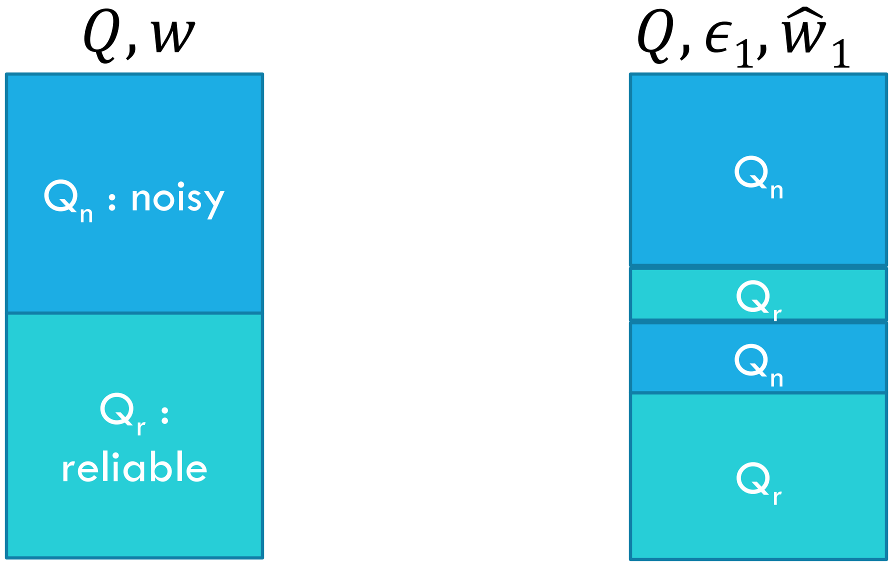
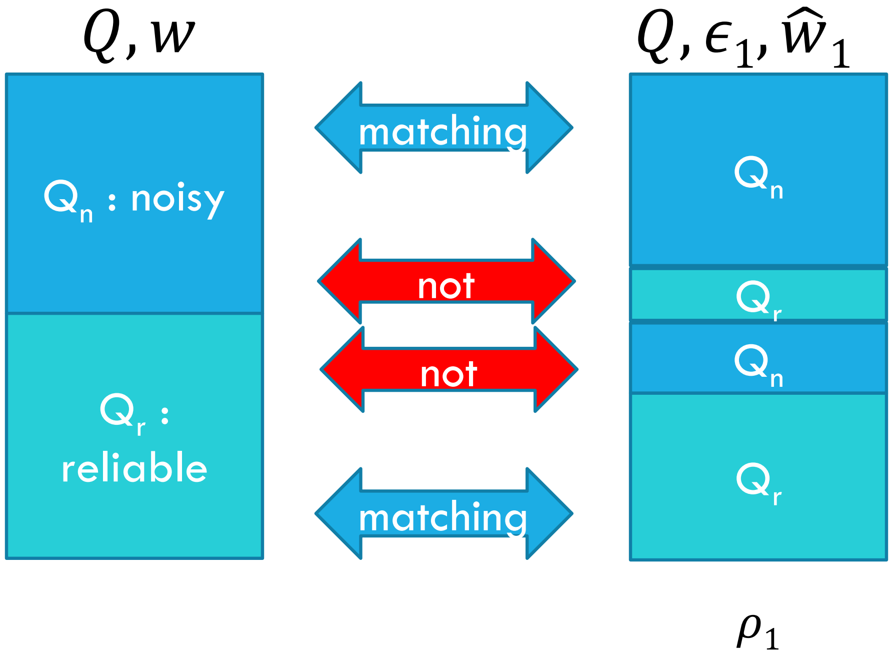
Reliability-based modeling attack on APUFs using CMAES [3]

Iteration 1



Reliability-based modeling attack on APUFs using CMAES [4]

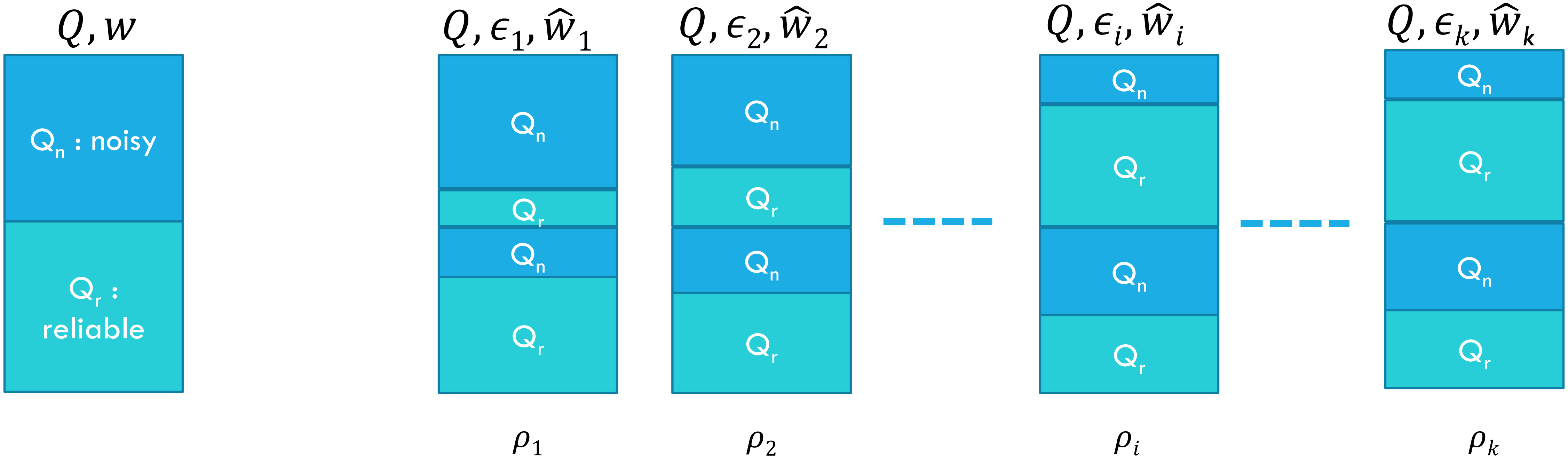
Iteration 1



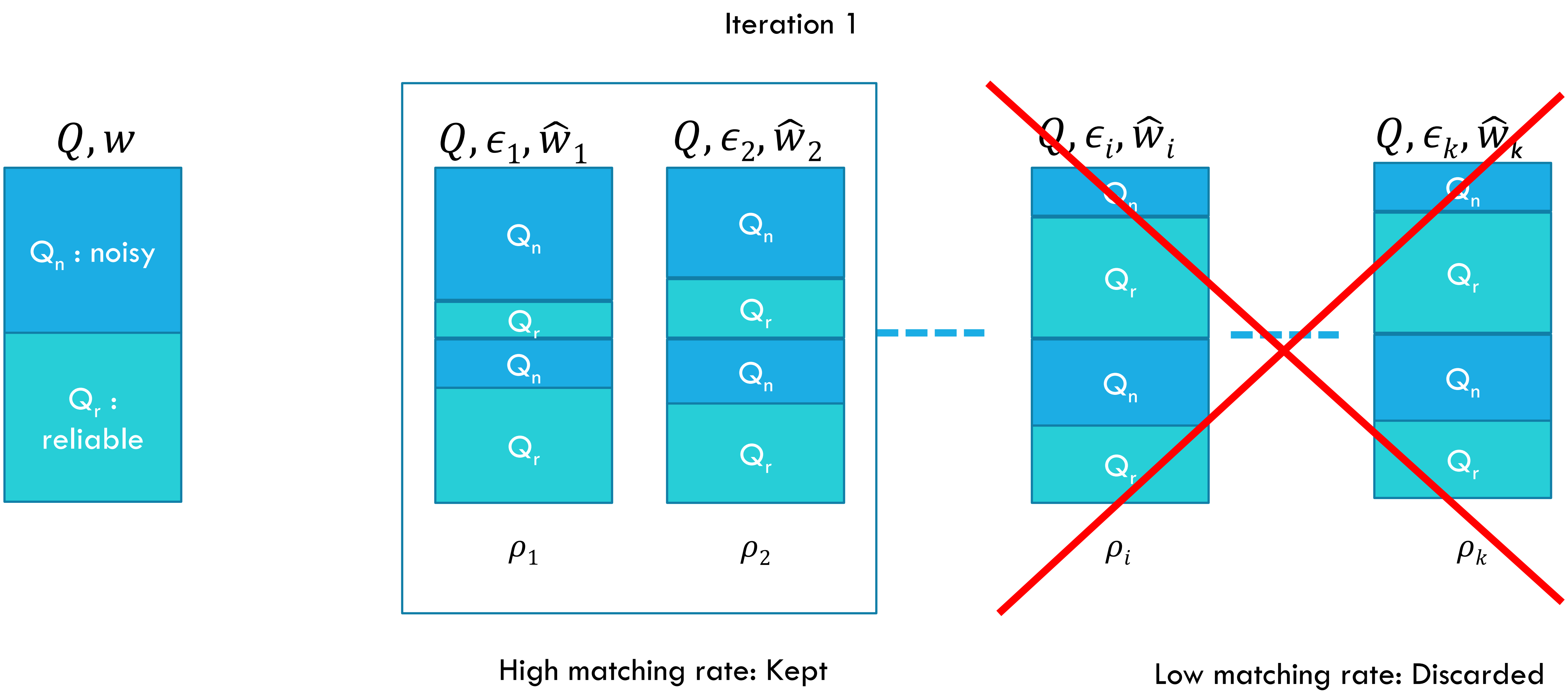
Compute the matching rate ρ_1 *between* $[Q, w]$ *and* $[Q, \epsilon_1, \hat{w}_1]$

Reliability-based modeling attack on APUFs using CMAES [5]

Iteration 1

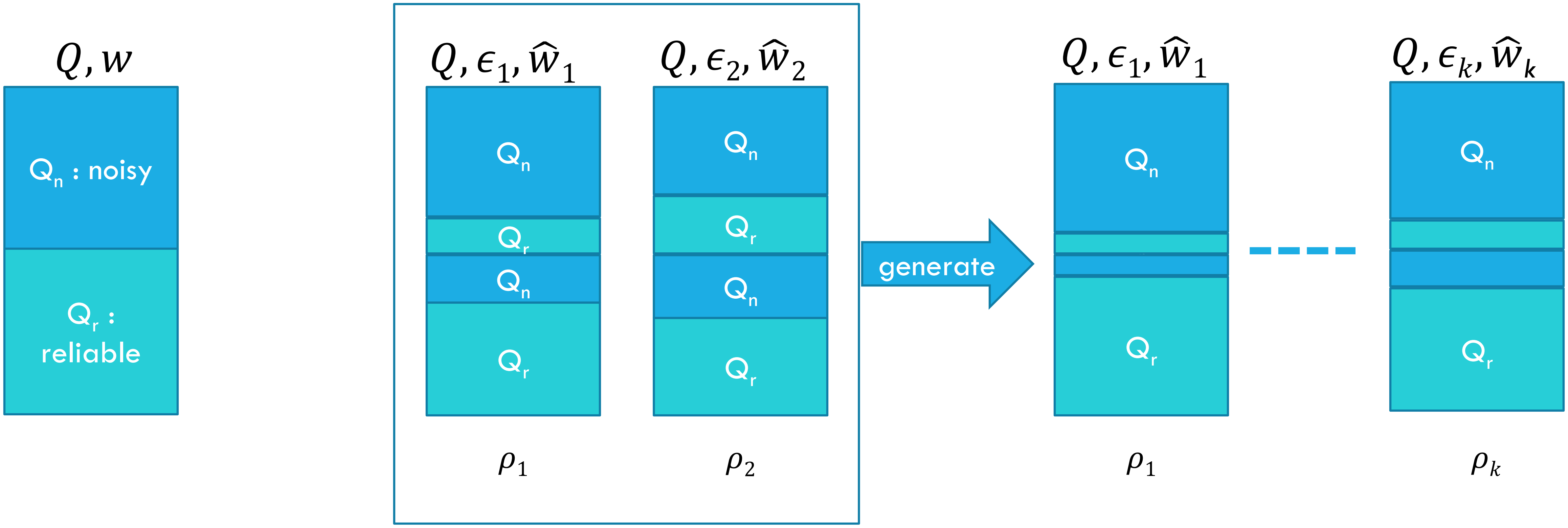


Reliability-based modeling attack on APUFs using CMAES [6]



Reliability-based modeling attack on APUFs using CMAES [7]

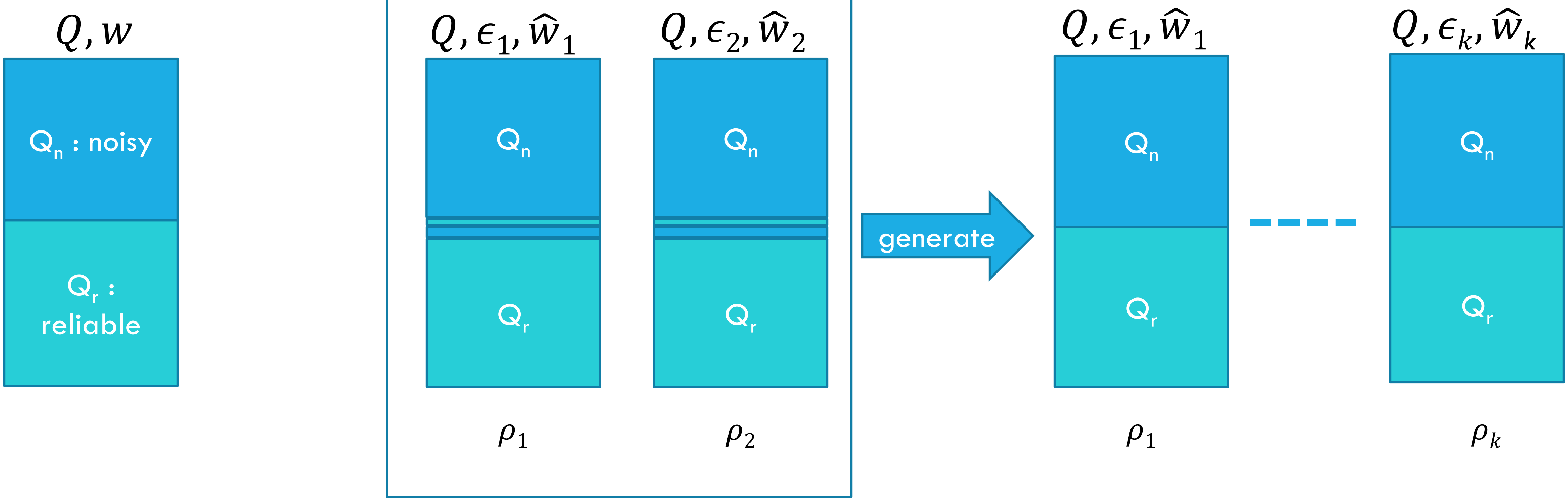
Iteration 2



High matching rate: Kept

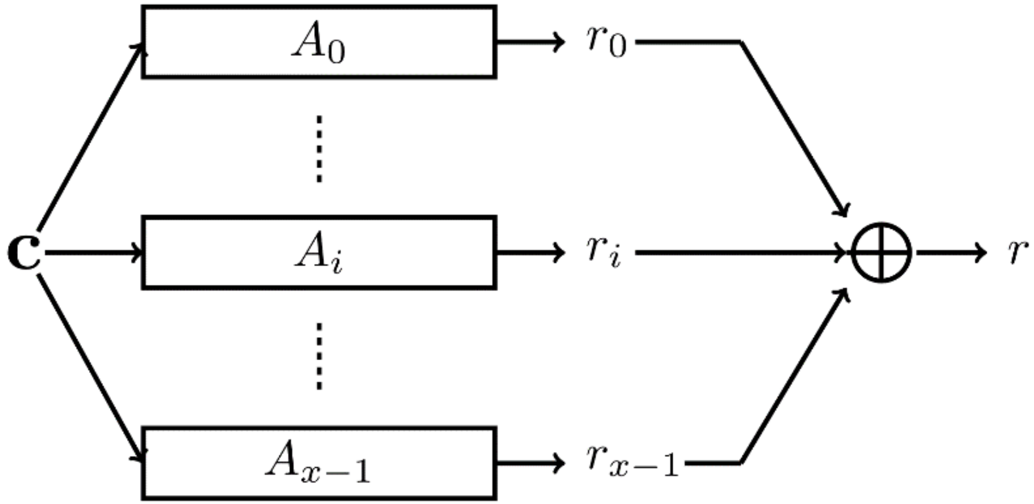
Reliability-based modeling attack on APUFs using CMAES [8]

Iteration M



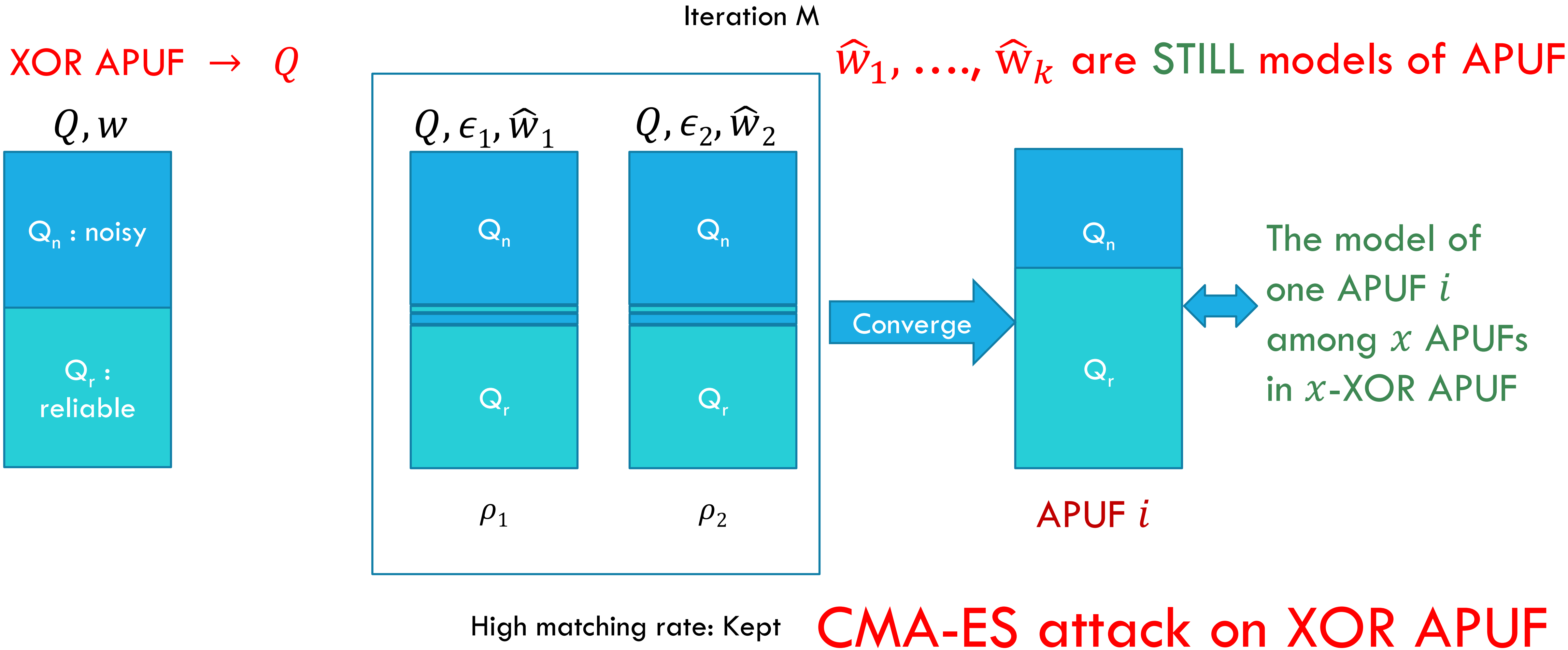
High matching rate: Kept

x-XOR APUF



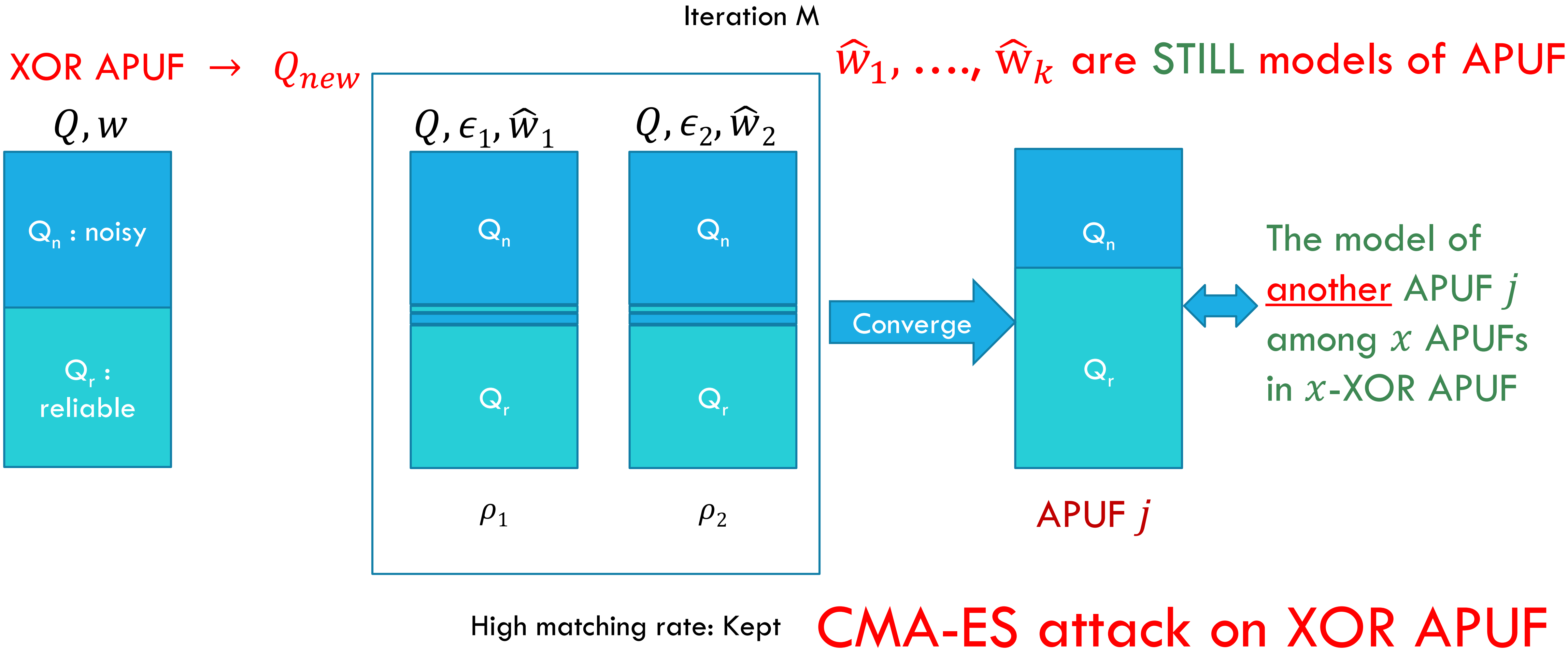
x-XOR PUF.

Reliability-based modeling attack on XOR APUFs using CMAES [1]



CMA-ES attack on XOR APUF

Reliability-based modeling attack on XOR APUFs using CMAES [2]



UCONN

Understanding Reliability based modeling attack on XOR PUF

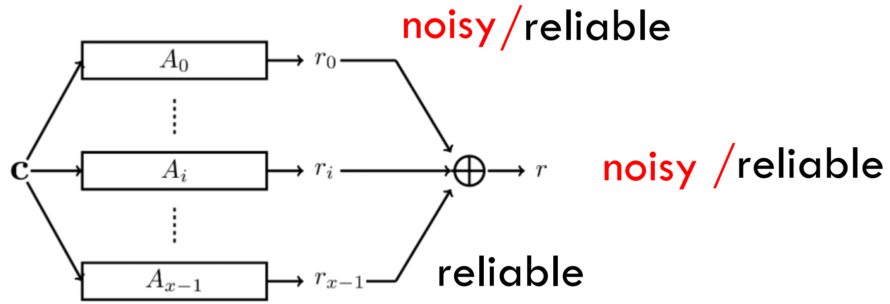
- Question 1: How does the attack on XOR PUF work?

- Question 2: How can we make the attack on XOR PUF fail?

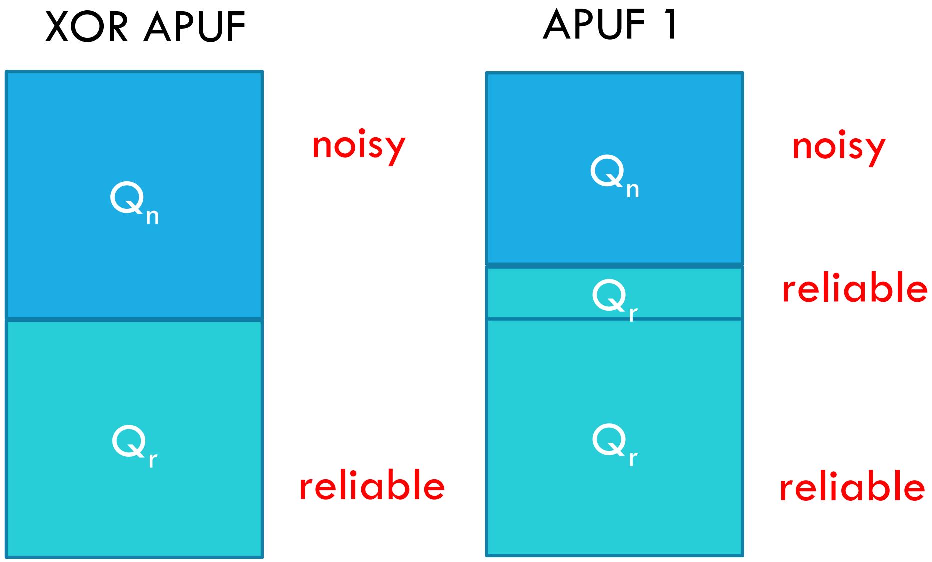
Question 1: How does the attack on XOR PUF work?

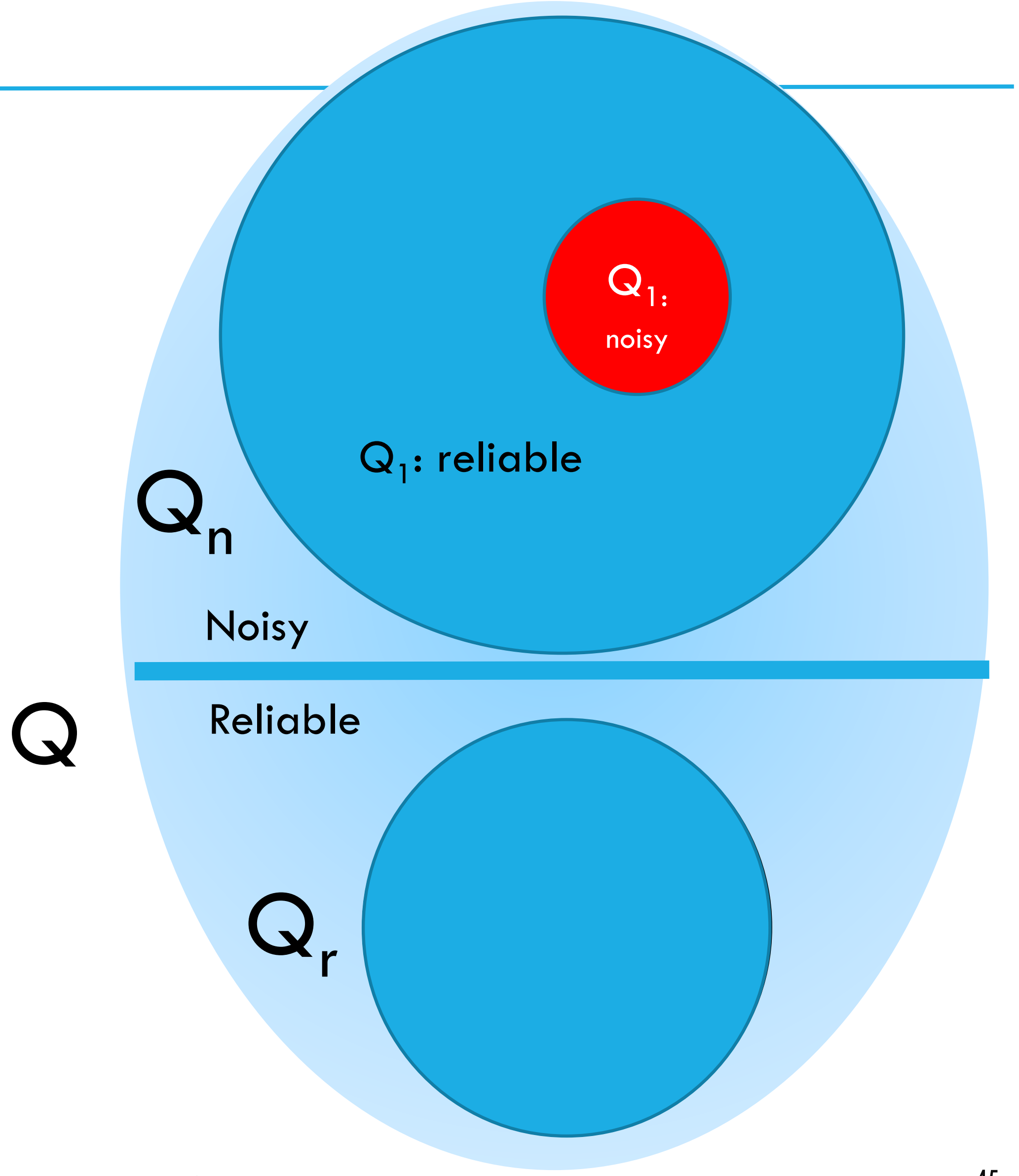
The noisy and reliable challenges in XOR PUF

UCONN



x-XOR PUF.

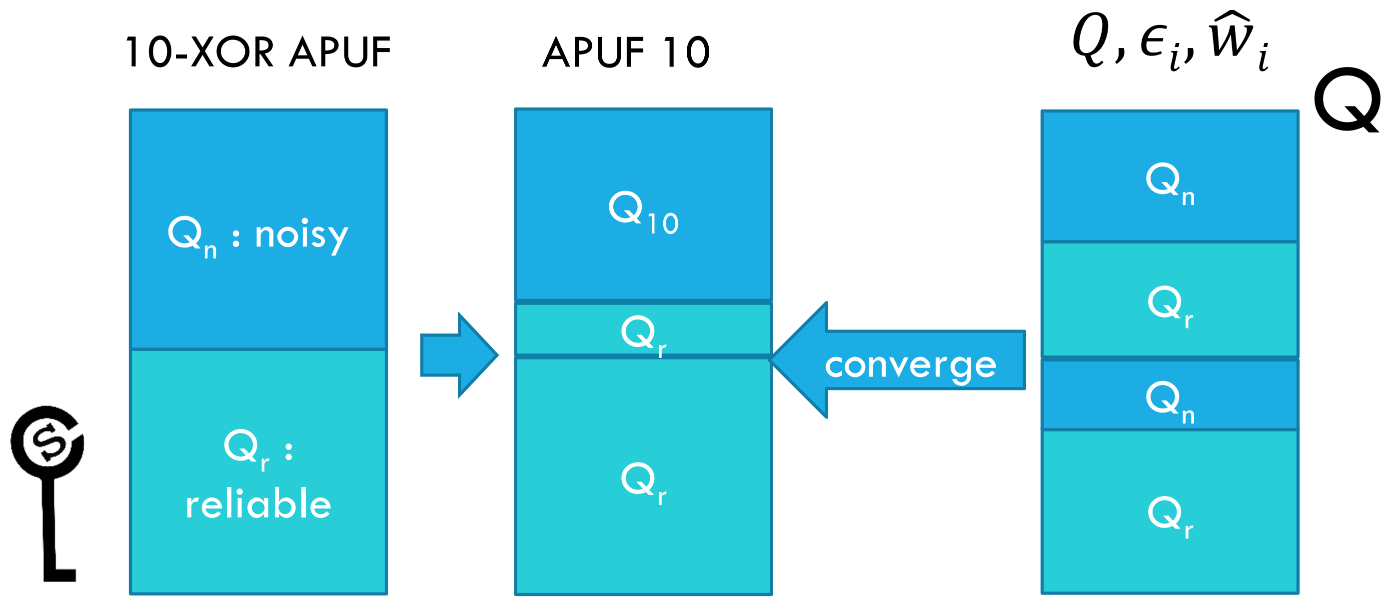


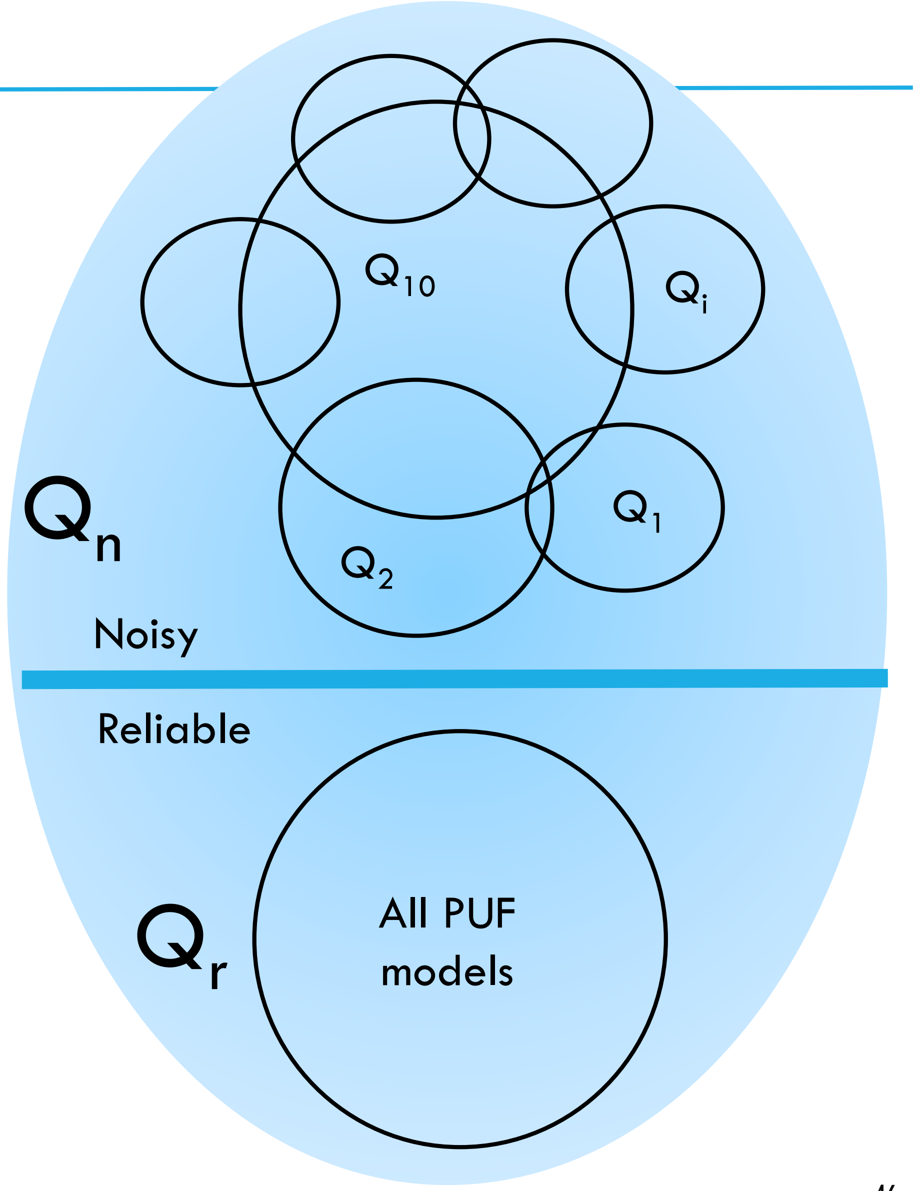


Challenge-Reliability Pairs Training Data

Key idea of the attack on XOR PUF [1]

- (1) All the models $\widehat{w}_i$ in CMA-ES are models of APUF





Challenge-Reliability Pairs Training Data

Key idea of the attack on XOR PUF [2]

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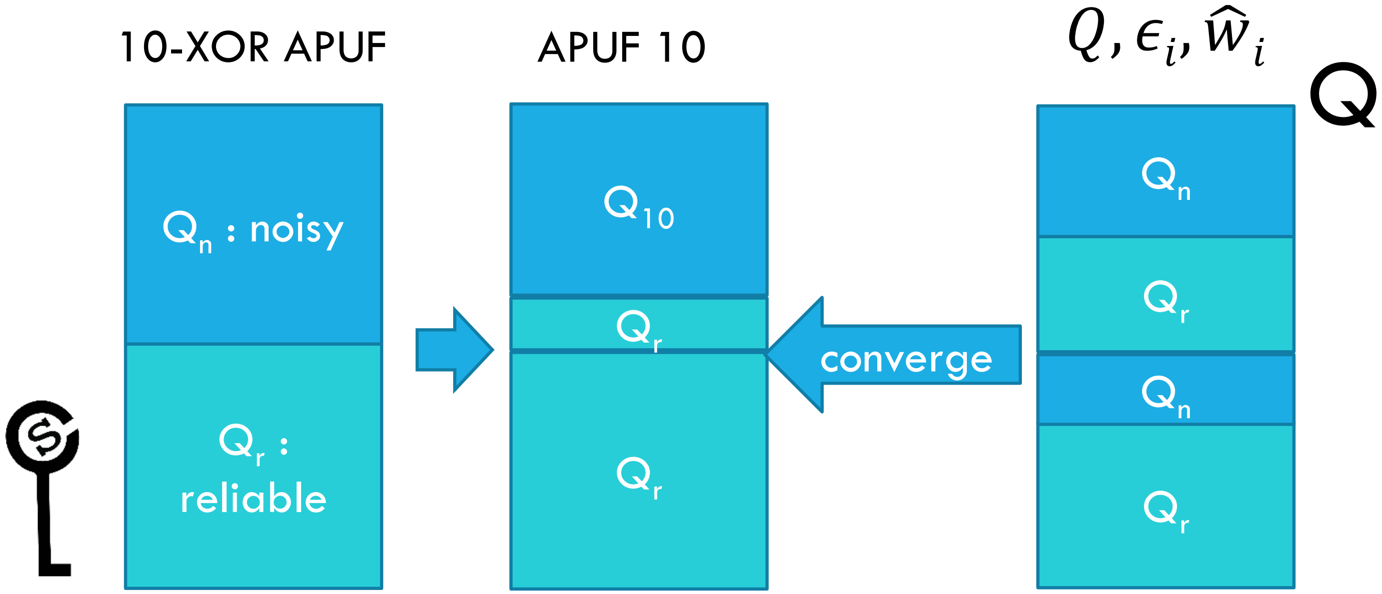
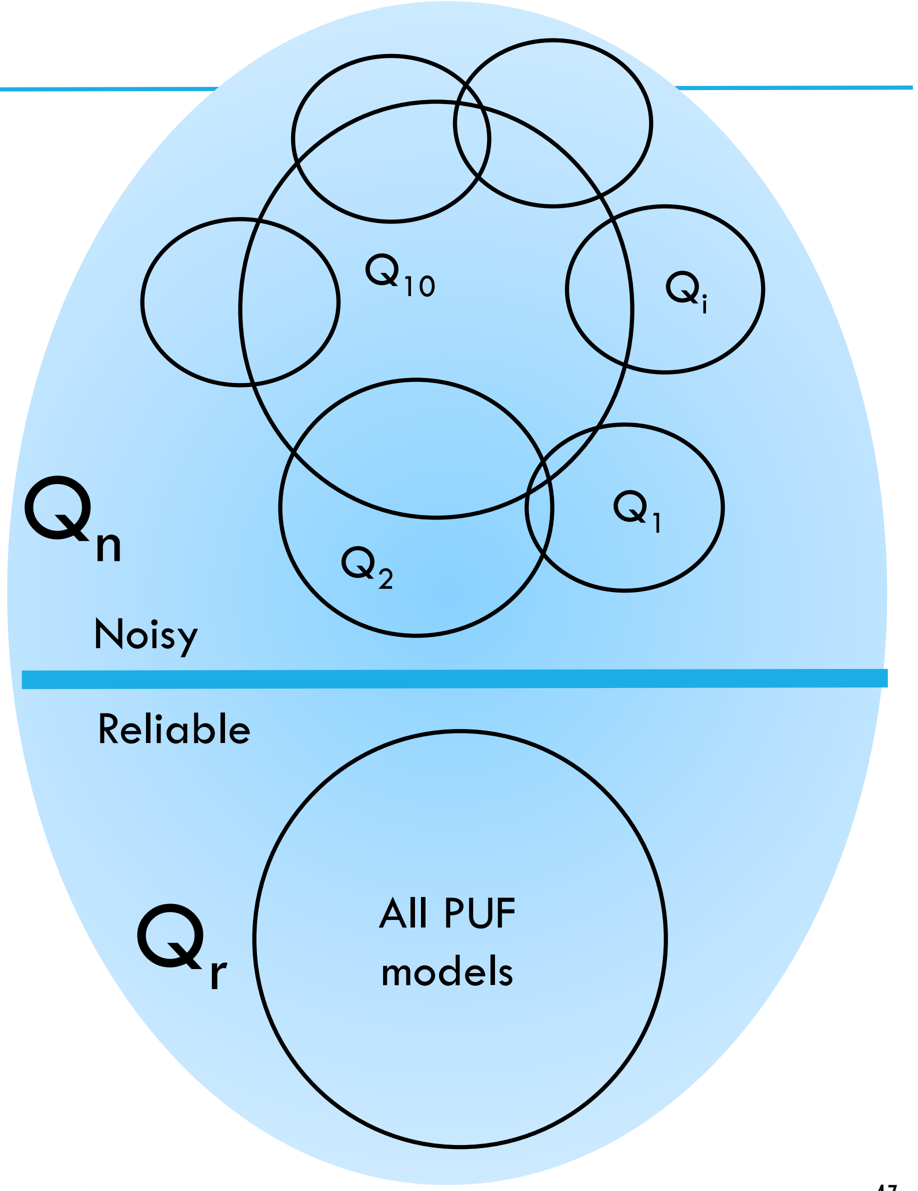
- (1) All the models $\hat{w}_i$ in CMA-ES are models of APUF
- (2) $\hat{w}_i$ can only converge to an APUF instance

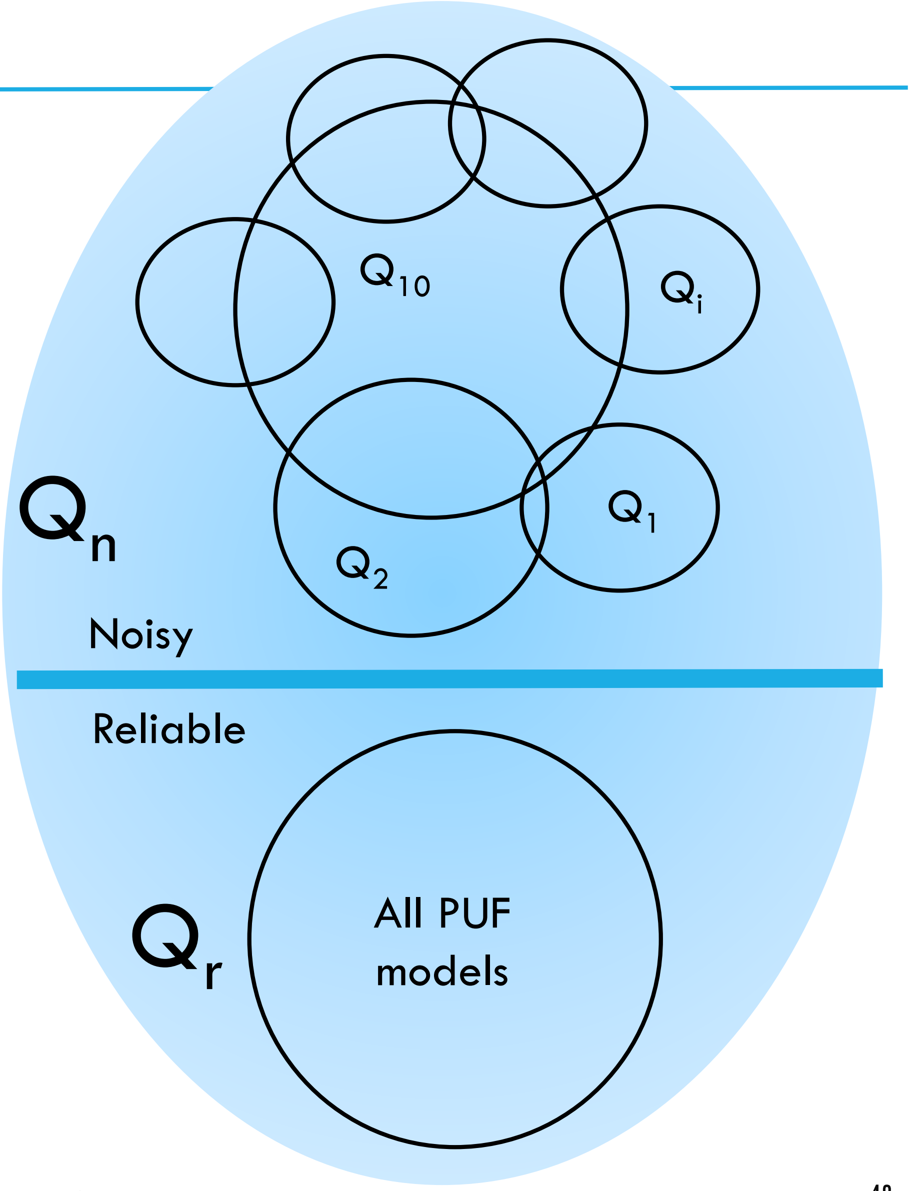




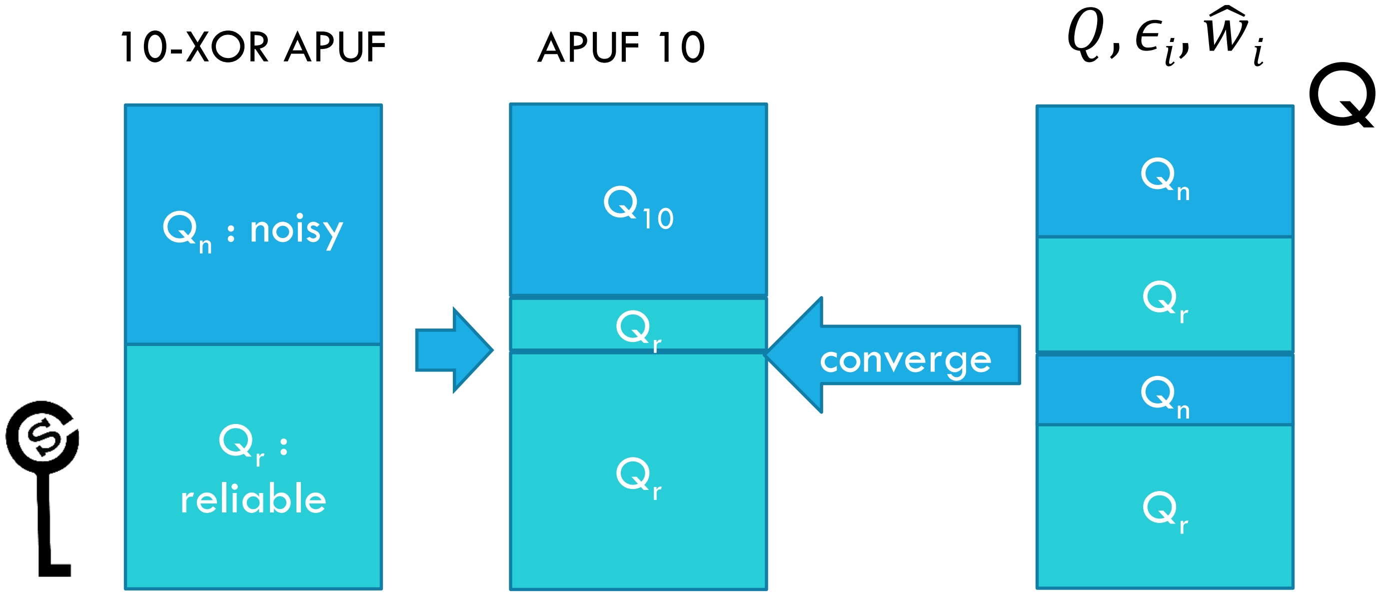
Challenge-Reliability Pairs Training Data

Key idea of the attack on XOR PUF [3]

- (1) All the models $\widehat{w}_i$ in CMA-ES are models of APUF
- (2) $\widehat{w}_i$ can only converge to an APUF instance
- (3) CMA ES maximizes the matching Q of $\widehat{w}_i$ and Q of XOR APUF

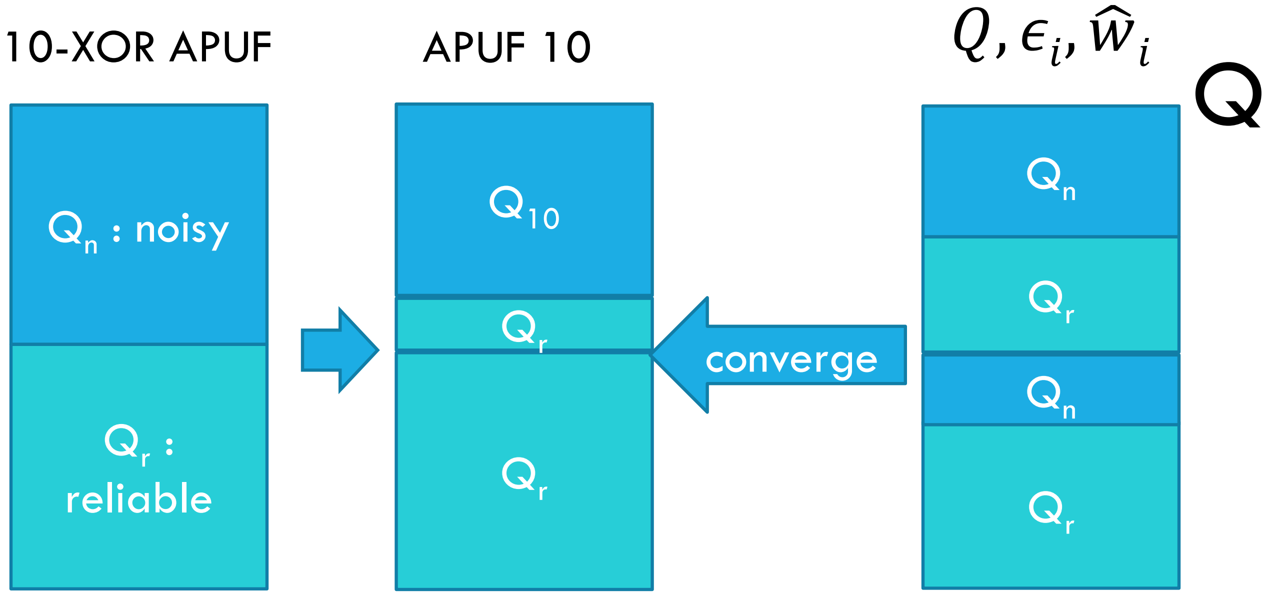


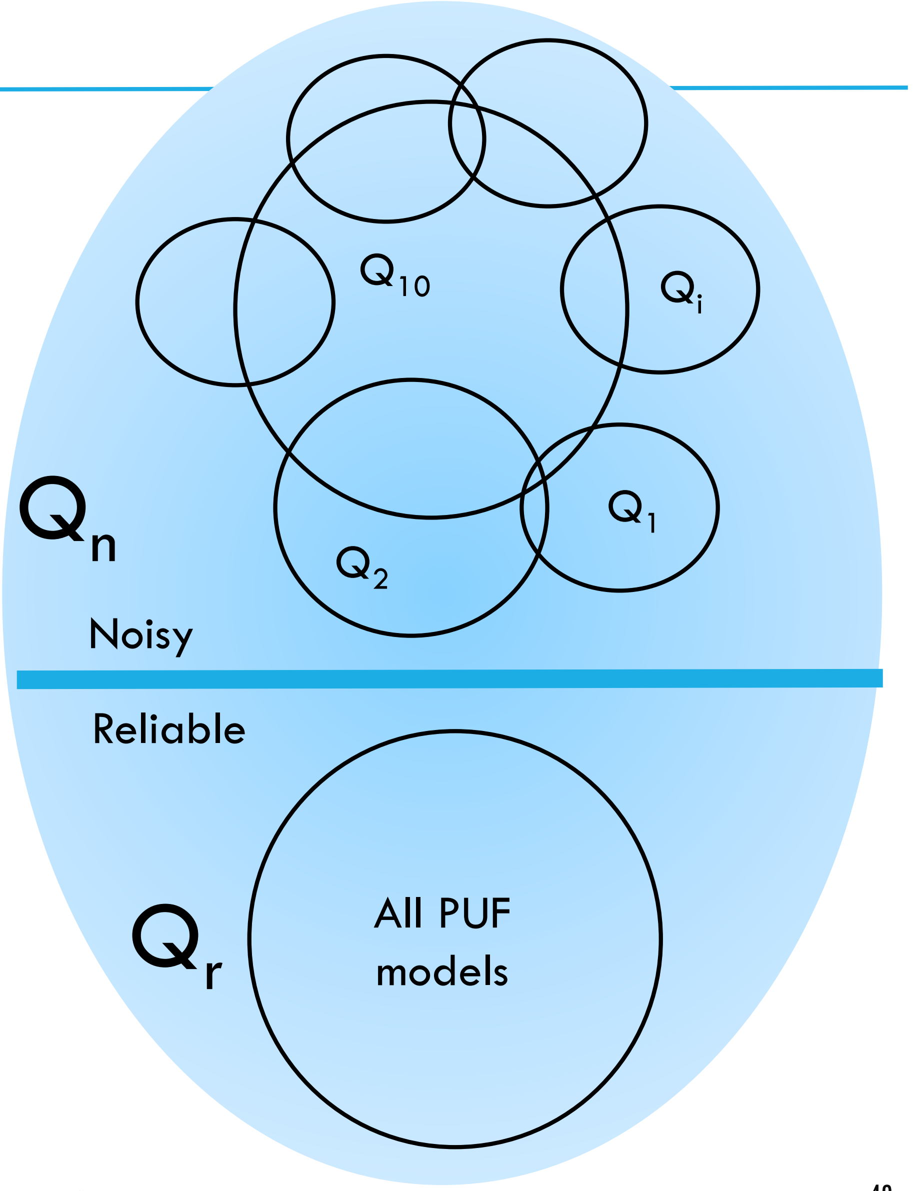
Challenge-Reliability Pairs Training Data



Key idea of the attack on XOR PUF [4]

- (1) All the models $\hat{w}_i$ in CMA-ES are models of APUF
- (2) $\hat{w}_i$ can only converge to an APUF instance
- (3) CMA ES maximizes the matching Q of $\hat{w}_i$ and Q of XOR APUF
- (1)+(2)+(3) CMA ES forces $\hat{w}_i$ converges to APUF 10 because Q of APUF 10 is the representative of Q of XOR APUF.





Challenge-Reliability Pairs Training Data

Key idea of the attack on XOR PUF [5]

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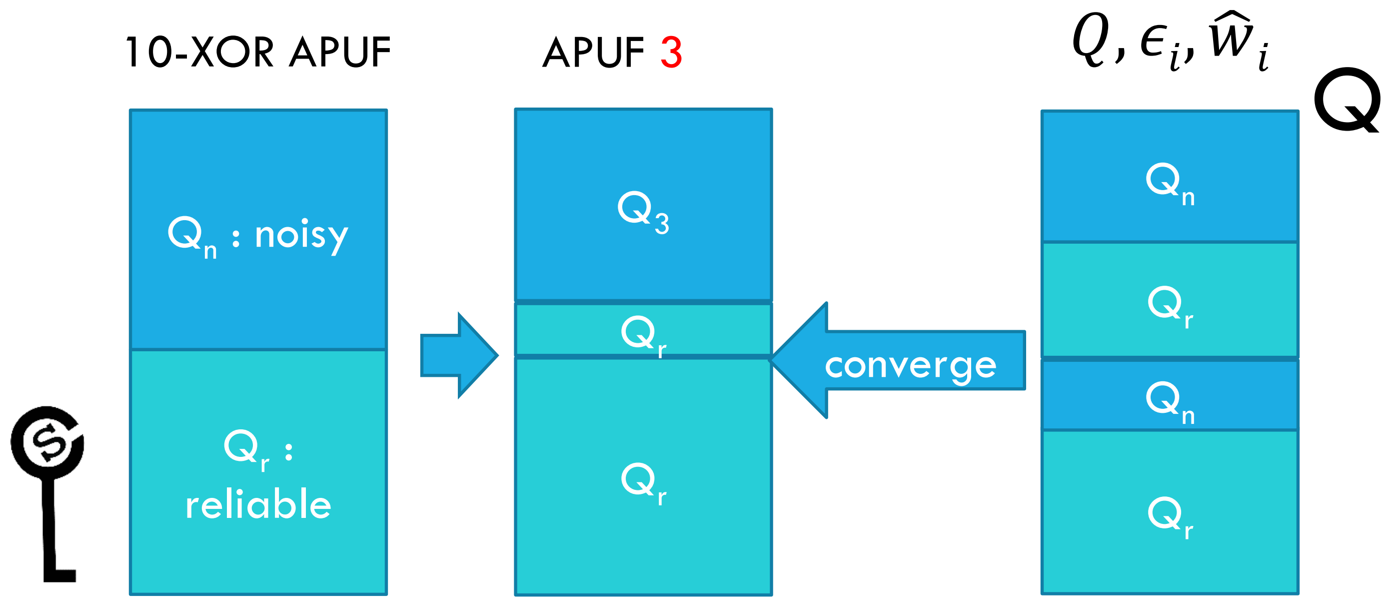
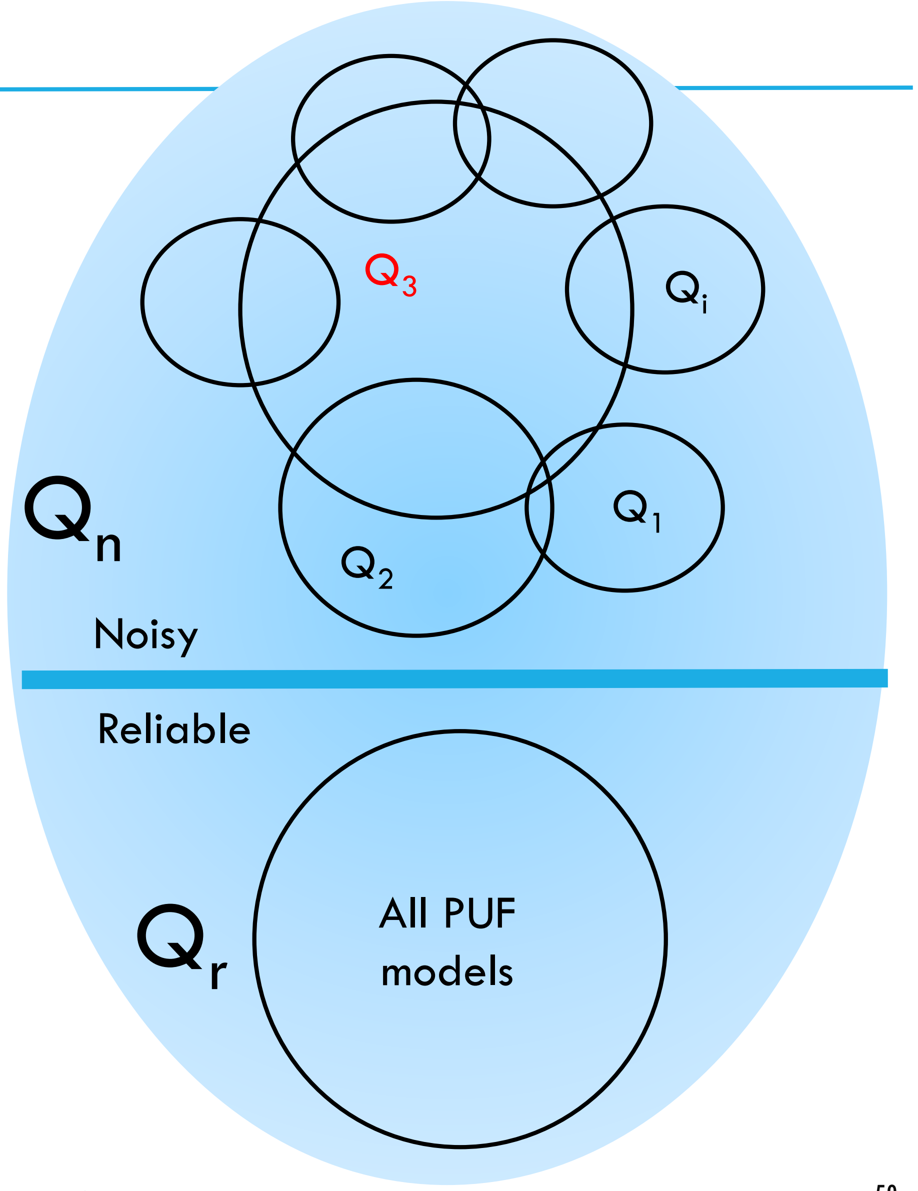
- Changing Q makes Q_3 largest



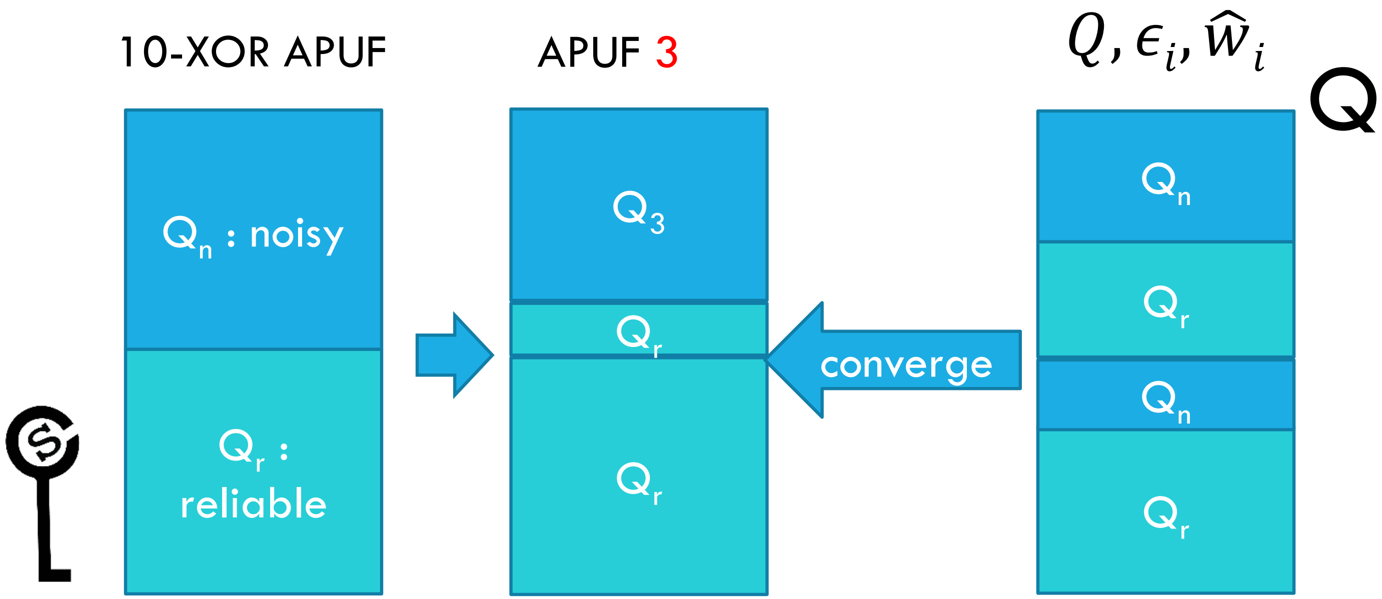


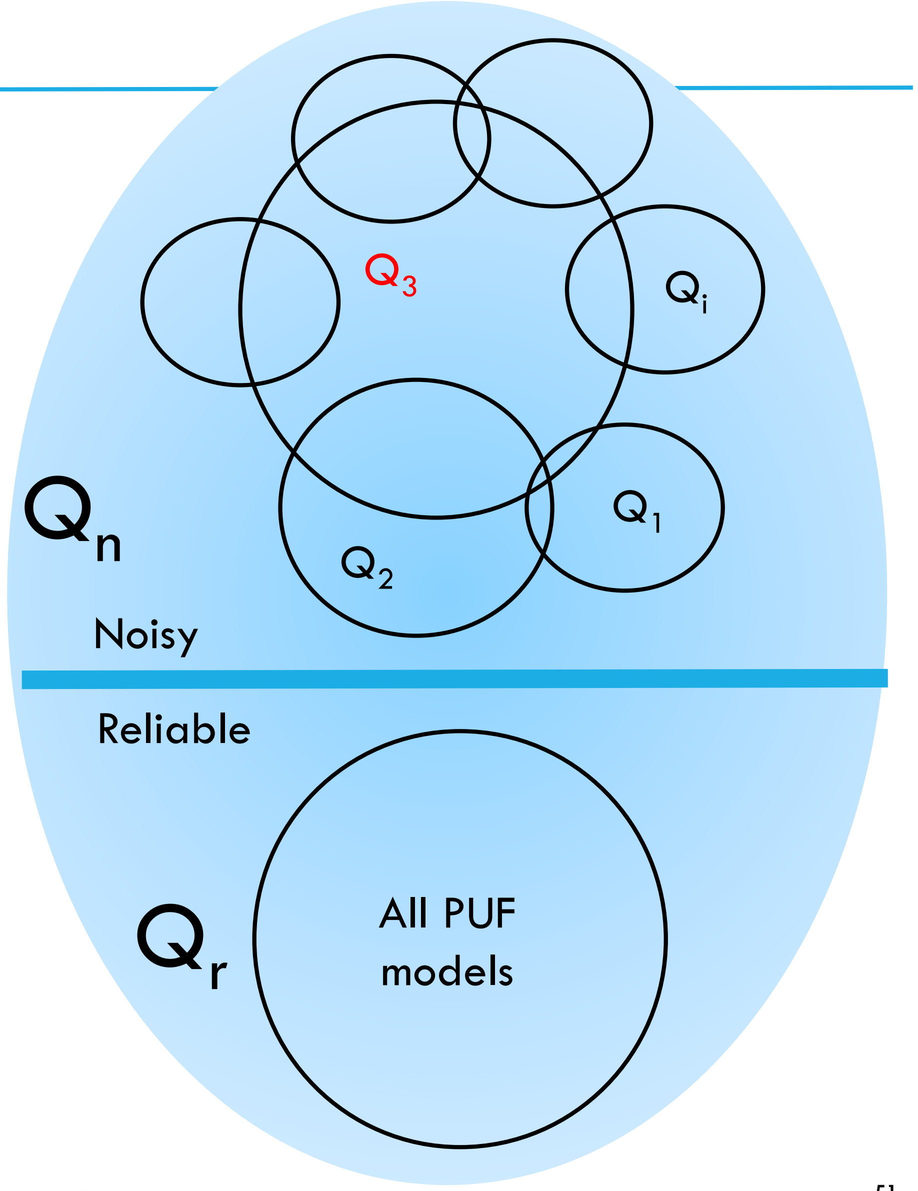
Challenge-Reliability Pairs Training Data

Key idea of the attack on XOR PUF [6]

- Changing Q makes Q_3 largest

Keep changing Q and applying CMA-ES attack on Q to get models of all APUF instances





Challenge-Reliability Pairs Training Data

Question 2: How to make the attack on XOR PUF fail?

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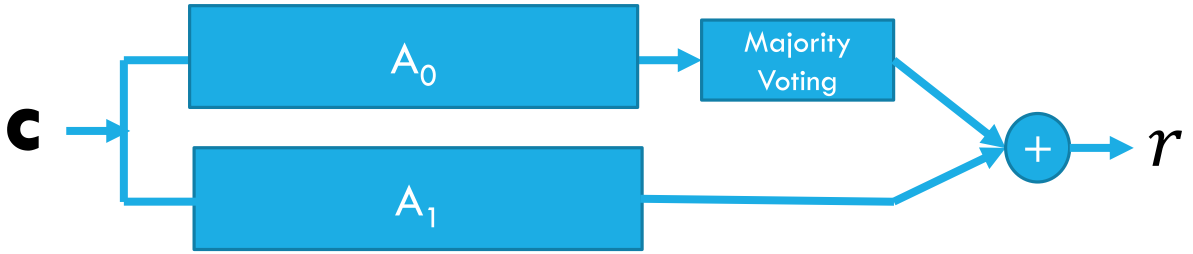
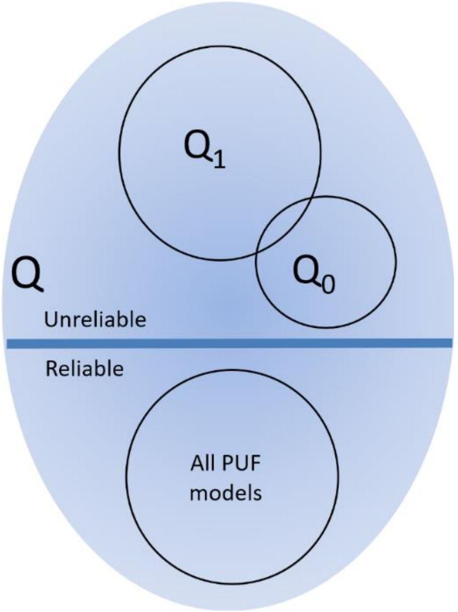
Attack fails



2-XOR APUF with majority voting circuit at A_0



CMA ES never converges to APUF A_0 and always converges to APUF A_1 when majority voting mechanism in use.

5. Interpose PUF (iPUF) – Reliability based modeling attack resistance

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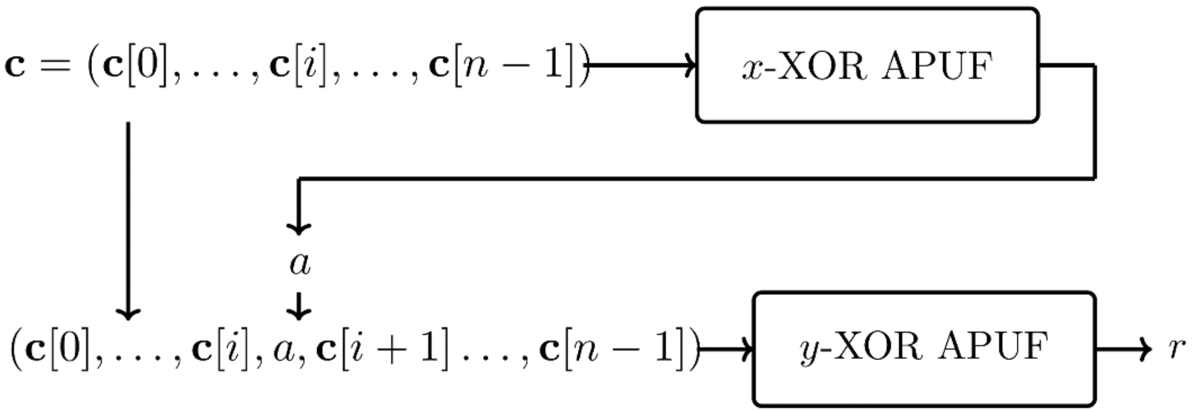
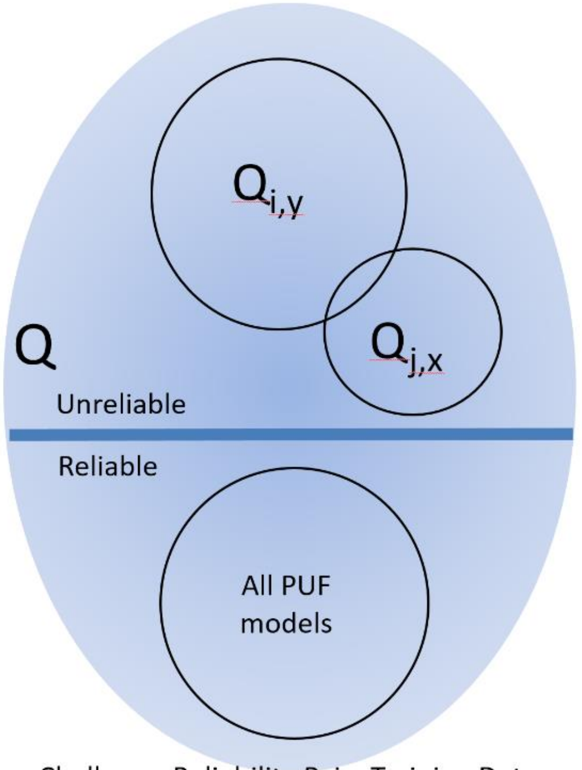
Security of iPUF wrt Reliability-based modeling attack [1]

- Reason 1: the information of APUF instances in x-XOR PUF presented at the iPUF output is less compared to APUF instances in y-XOR PUF. Thus, the reliability based modeling attack never converges to any APUF instance in x-XOR PUF

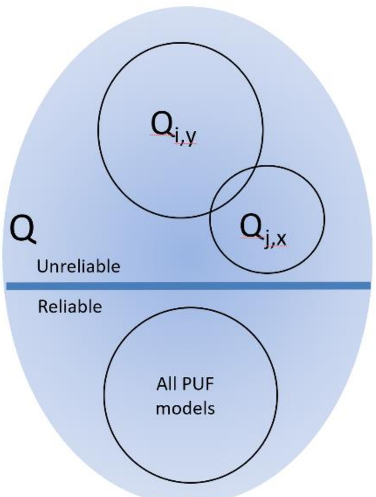




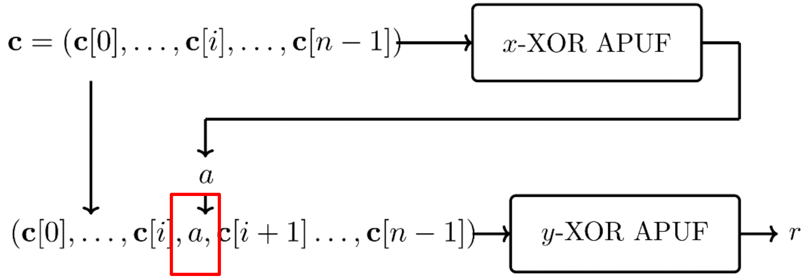
Challenge-Reliability Pairs Training Data

Security of iPUF wrt Reliability-based modeling attack [2]

- Reason 2: to attack APUFs at y-XOR APUF, the adversary needs to compute Δ. But compute Δ is infeasible because the output of x-XOR PUF (a) is not known.



Challenge-Reliability Pairs Training Data



$Q, \epsilon_1, \hat{w}_1$

Cannot compute $\Phi(c)$ or Δ

$Q \rightarrow challenge\ c \rightarrow \Phi(c) \rightarrow \Delta = \hat{w}_1 \cdot \Phi(c)$

$|\Delta| \leq \epsilon_1 \rightarrow$ *challenge c is noisy* → Q_n : noisy

$|\Delta| > \epsilon_1 \rightarrow$ *challenge c is reliable* → Q_r : reliable

$$\Delta = \Delta(n-1) = \mathbf{w} \cdot \mathbf{\Phi}^{\mathsf{T}}$$

$$\mathbf{\Phi}[i] = \prod_{j=i,\ldots,n-1} (1 - \mathbf{c}[j]), i = 0, \ldots, n-1$$

$$\mathbf{\Phi}[n] = 1$$

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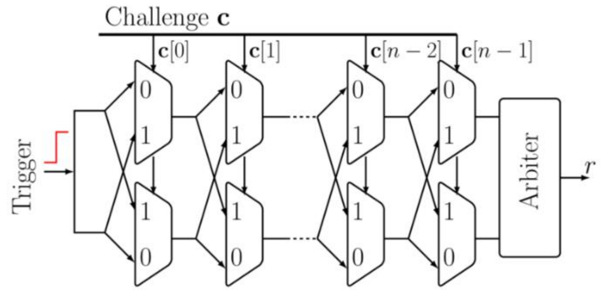
Other Contributions

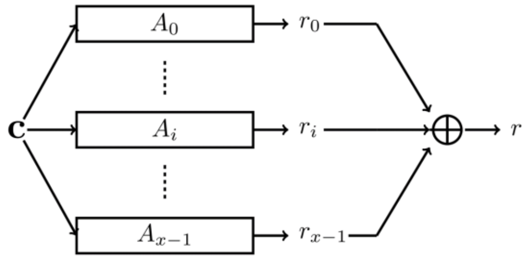
- Theoretical
  - Enhanced Reliability based Modeling Attacks on APUF and XOR APUFs
  - Proved Logistic Regression on XOR APUF is the best attack
  - Proved Logistic Regression on iPUF is not applicable
- Engineering
  - Implemented APUF, XOR, and iPUF on FPGA
  - Studied good and bad FPGA-implemented APUF based PUF
  - All source codes available online: https://github.com/scluconn/DA_PUF_Library/
- Detailed tutorial online: https://www.youtube.com/playlist?list=PLK5NNs4GceLQw7bOEHSdZOwHlmSF1zvSW

6. Conclusion

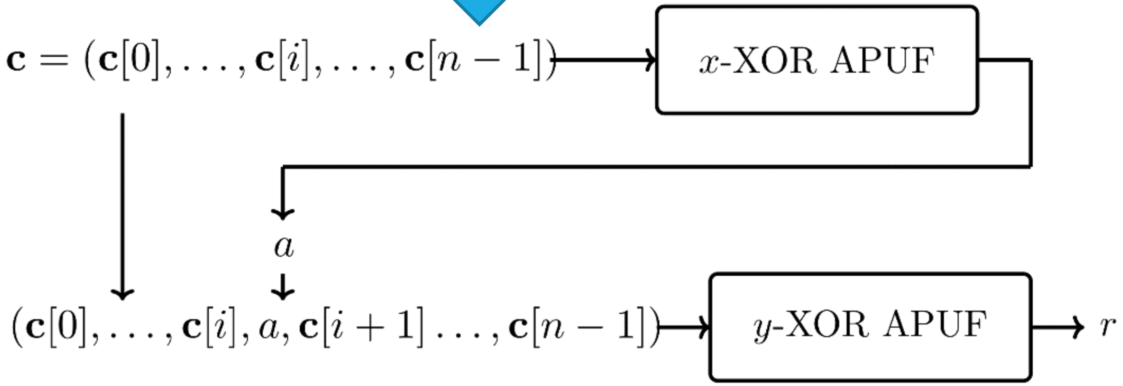
- We explain how the reliability-based modeling attack on XOR PUF works
- We propose a new lightweight PUF design (iPUF) which is secure against the state-of-the art of modelling attacks.



A n-stage classic Arbiter PUF with challenge $\mathbf{c} \in \{0,1\}^n$.



x-XOR PUF.



UCONN

Literature

1. https://slideplayer.com/slide/3927633/
2. Cryptanalysis of electrical PUFs via machine learning algorithms – Master Thesis of Jan Solter
3. The Gap Between Promise and Reality: On the Insecurity of XOR Arbiter PUFs CHES, September 16 th , 2015, Georg T. Becker
4. https://en.wikipedia.org/wiki/CMA-ES

Thank you for your attention!

and any questions?