Privacy-preserving methods: multimedia and biometrics perspectives

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http://sip.unige.ch/education/multimedia-security/

Lecture Outline

- Introduction: privacy and security in biometrics and multimedia
- Cryptographic approach
- Signal processing approach
- Hybrid approach

Information security

- Personal Identier Number (PIN): to control access to service, systems and information

- Subscriber Identity Module (SIM): access to mobile phones, to protect against illegal use of network

- Secure Socket Layer (SSL): to prevent eavesdropping on information exchanged between two terminals

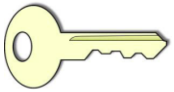
Traditional cryptography

Cryptography: develops tools for protecting information and establishing secure interactions.

- Encryption: provides confidentially of information
- Authentication: verifies the identity

Note: The algorithms are public, therefore, the security of the schemes depends on the secrecy of a key owned by the legitimate parties.

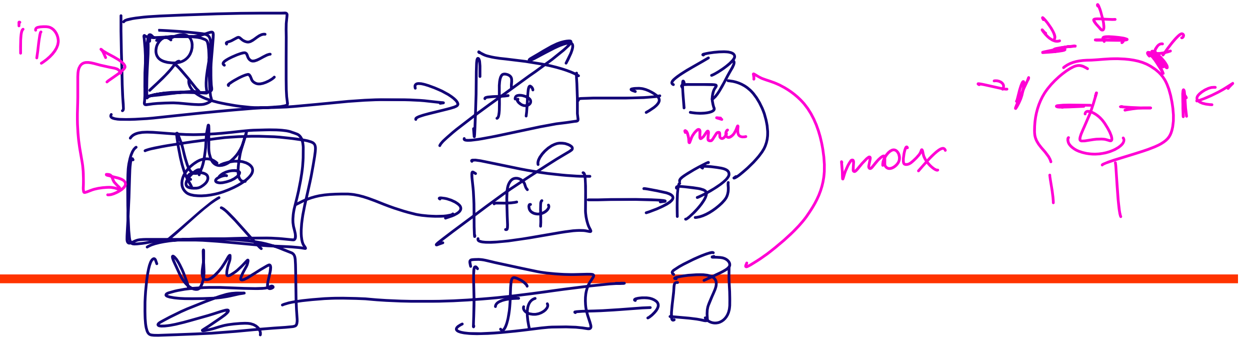
Practical cryptography issues in our modern society:

1 Key generation and distribution 

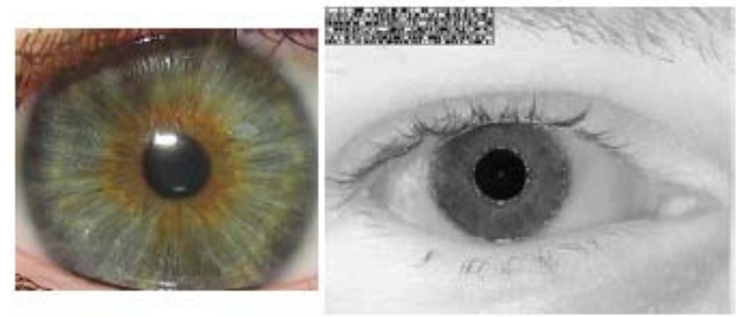
2 Safely storage: (mobile phones, bank tokens, smart cards, : : :) 

3 Noisy observation: authentication based on something closely linked to physiological characters 

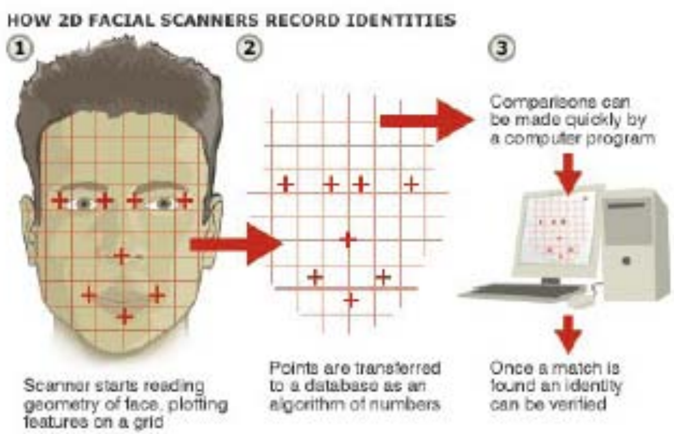
Biometrics



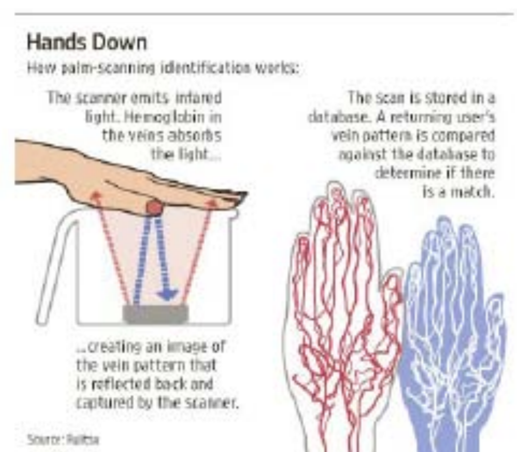
Fingerprint



Iris



Facial



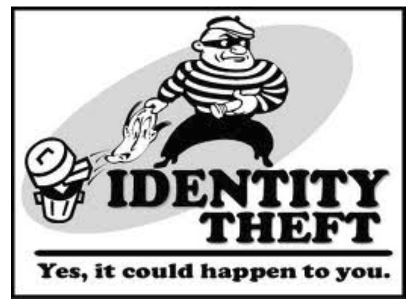
Palm vein

Biometrics: why to be protected?

A biometric template is a representation of a unique characteristic of an individual. It might also contain some information about diseases. Therefore, it contains privacy-sensitive information.

To abuse database:

- impersonation
- identity theft
- cross-database matching
- detectable pathologies
- … yet undiscovered attacks

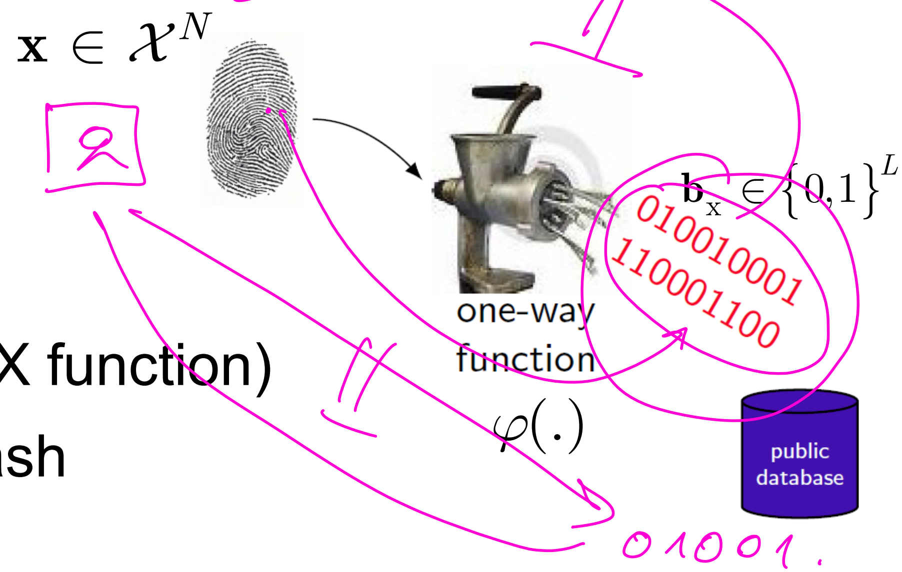


Note: biometric templates can not be "cancelable" because people have only ten fingers, two eyes, etc.

15:10.

Mutimedia security: cryptographic solution

- Main idea:
  - do not store date itself
  - store a one-way hash
    (non-invertible function like UNIX function)
  - for the same data, the same hash



Remark: the hash $\varphi(.)$ is assumed to be uninformative $\Rightarrow$ non-invertible.

(which is not true in information-theoretic sense).

X Y

$I(X;Y)=0$ $\quad$ $I(X;Y)>0$

B_x

$$\underbrace{I\left(X;h\left(X\right)\right)=0}$$

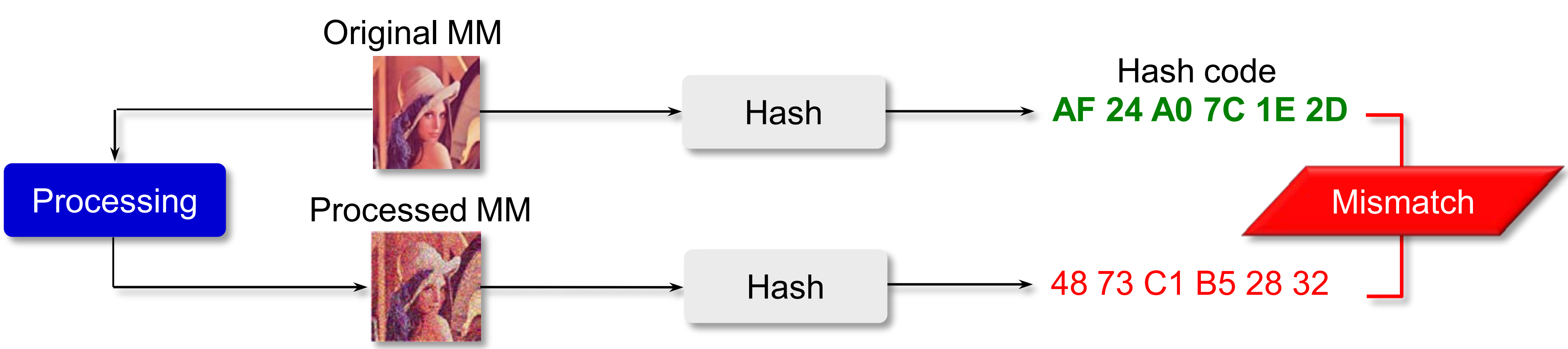
This is not true, since $h(X)$ is a function of X!

$b_x = h(x)$

Mutimedia security: cryptographic solution

Why are traditional security tools not suitable for multimedia?

- Traditional *security*:
  - Cryptographic encryption (confidentiality of information)
  - Cryptographic hashes (authentication, trust, access control)
- Main concerns of classical crypto-based algorithms:
  - Sensitivity to noise and unintentional distortions in input data
  - Data handling in the encrypted domain



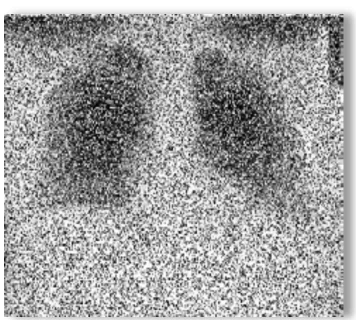
Mutimedia privacy: data «degradation»

Why are traditional privacy tools not suitable for multimedia?

- Traditional *privacy protection* [1]:
  - Data owner (protect data): based on data degradation and randomization (noise addition, lossy compression, data removal, dim. reduction…)
  - Data user (protect requests): based on anonymization, randomized rules
- Main concerns of classical privacy preserving algorithms:
  - Reduction of accuracy (data utility)
  - Not very efficient against experienced attackers (sensitivity analysis)

Original

50% removed based on key



Median 9x9

Adaptive recovery

[1] C. Aggarwal and P. Yu, Privacy-Preserving Data Mining: Models and Algorithms, Spinger, 2008.

Dinov2.
SSL.

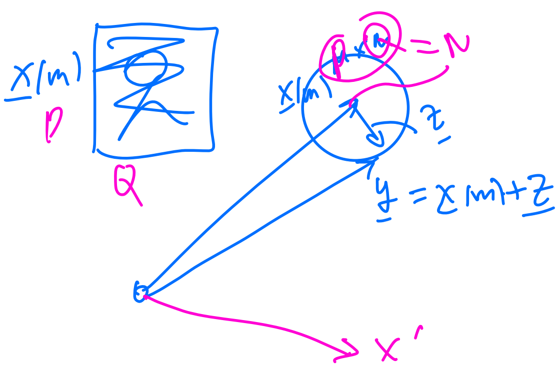
Signal processing approach: authentication

- Use hypothesis testing
- Handle noisy data $\Rightarrow$ extended decision region

$$\begin{cases} H_0 : \mathbf{y} = \mathbf{x}' + \mathbf{z}, \\ H_1 : \mathbf{y} = \mathbf{x}(m) + \mathbf{z}, \end{cases}$$

$$\mathbf{x}' \neq \mathbf{x}(m), \text{any } 1 \leq m \leq |\mathcal{M}|$$

8 Mio



Crypto

$\mathbf{x}(m) = \mathbf{y}$

Hash region

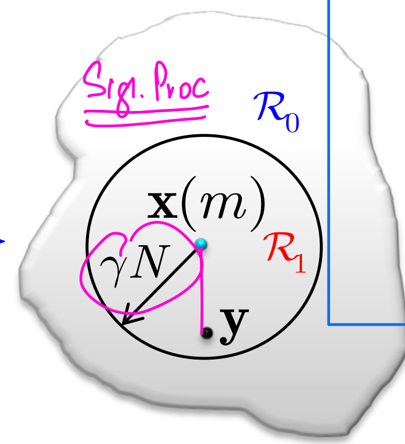
$\varphi(.)$

$\| x(m) - y \|_2^2 = 0$

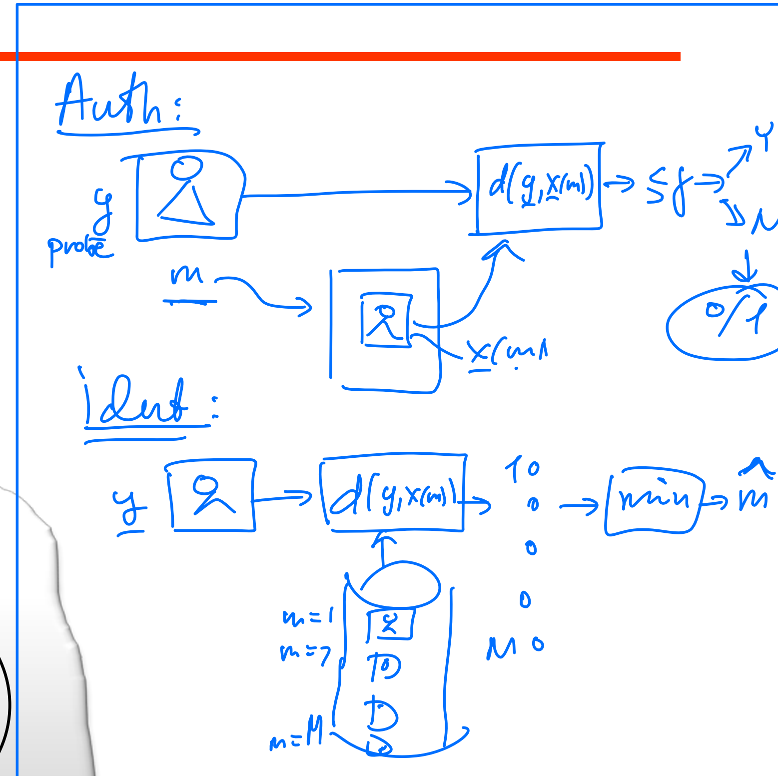
$\| \varphi(x(m)) - \varphi(y) \|_2^2 = 0$

$\neq$

$\Rightarrow$



Decision region



Gaussian assumption $\Rightarrow$ Euclidian distance $\equiv$ Sphere region

$$\mathcal{R}_1 : d^E\left(\mathbf{y}, \mathbf{x}(m)\right) = \left\|\mathbf{y} - \mathbf{x}(m)\right\|^2 \leq \gamma N \quad \Rightarrow \quad \mathcal{R}_1 : \mathbf{y}^T\mathbf{x}(m) \geq \gamma' N$$

$(a-b)^2 = a^2 - 2ab + b^2$

$\|y\|_2^2 - 2y^T x(m) + \|x\|_2^2$

Signal processing approach: authentication

$$\mathcal{R}_1 : \boxed{\mathbf{y}^T\mathbf{x}(m)} \geq \gamma' N$$

x'

H_0: $x^T \underline{x}(m)$, y^T

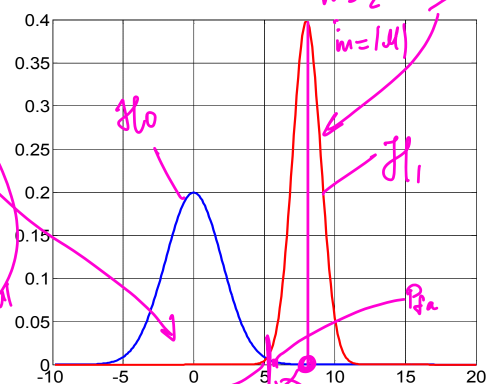
H_1: $x^T(m)\,\underline{x}(m) = \|\underline{x}(m)\|_2^2$

$(x^T(m)+z)\,\underline{x}(m)$

$= x^T(m)\,\underline{x}(m) + z^T \underline{x}(m)$

$\|x(m)\|_2$

m=1
m=2
m=|M|



γ'

$$\rho = \frac{\mathbf{y}^T\mathbf{x}(m)}{\cancel{N}}$$

Bayes → P_e

N-P fix P_{fa} → P_m.

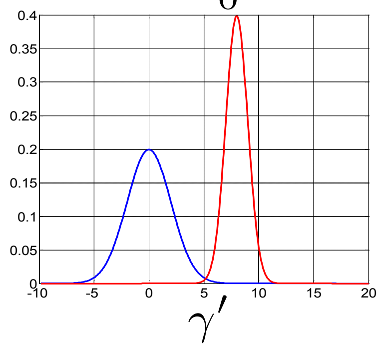
$$P_f = \Pr\left[\mathbf{y}^T\mathbf{x}(m) \geq \gamma' N \,\middle|\, H_0\right] - \text{probability of false accaptance}$$

$$P_m = \Pr\left[\mathbf{y}^T\mathbf{x}(m) < \gamma' N \,\middle|\, H_1\right] - \text{ probability of miss}$$

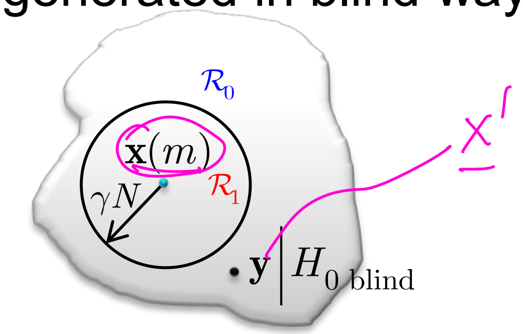
Signal processing approach: authentication

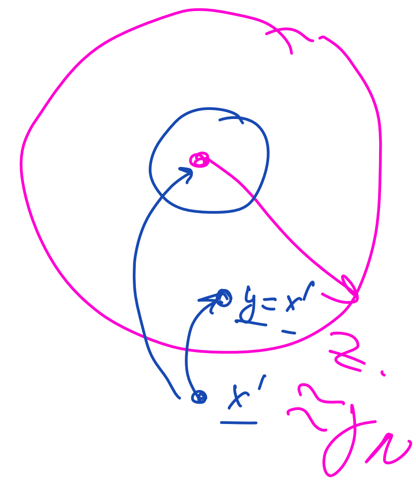
Blind attacks

- $\mathbf{x}'$ under H_0 was assumed to be generated in blind way



$$\rho = \frac{\mathbf{y}^T \mathbf{x}(m)}{N}$$



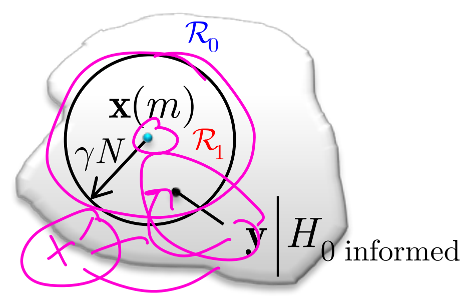


Informed attacks

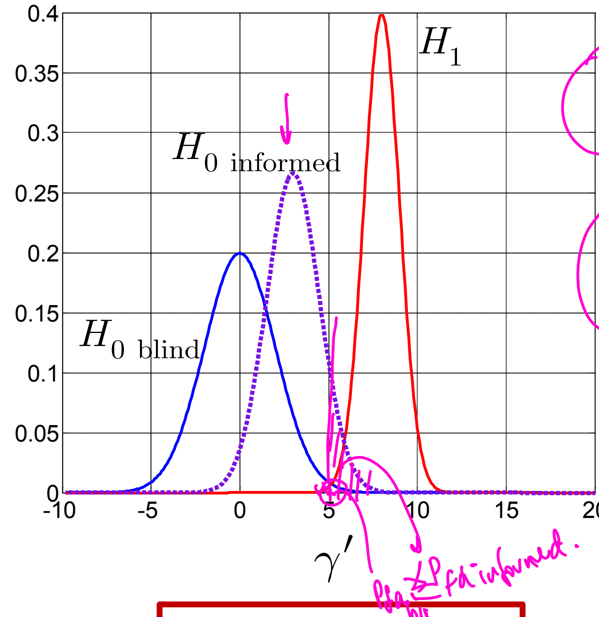
- Attacker can generate $\mathbf{x}'$ as close as possible to $\mathbf{x}(m)$, if it is disclosed!

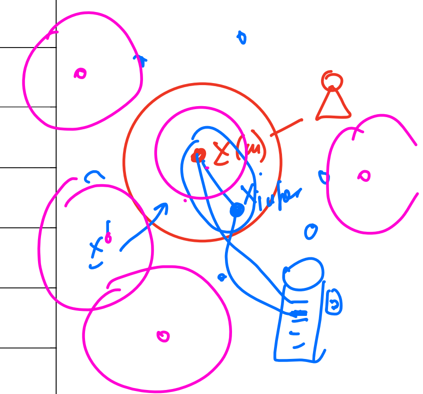
$$P_f = \Pr\left[\mathbf{y}^T \mathbf{x}(m) \geq \gamma' N \,\middle|\, H_0 \text{ blind}\right]$$

$$P_{sa} = \Pr\left[\mathbf{y}^T \mathbf{x}(m) \geq \gamma' N \,\middle|\, H_0 \text{ informed}\right] - \text{prob. of succ. attack}$$



Signal processing approach: authentication





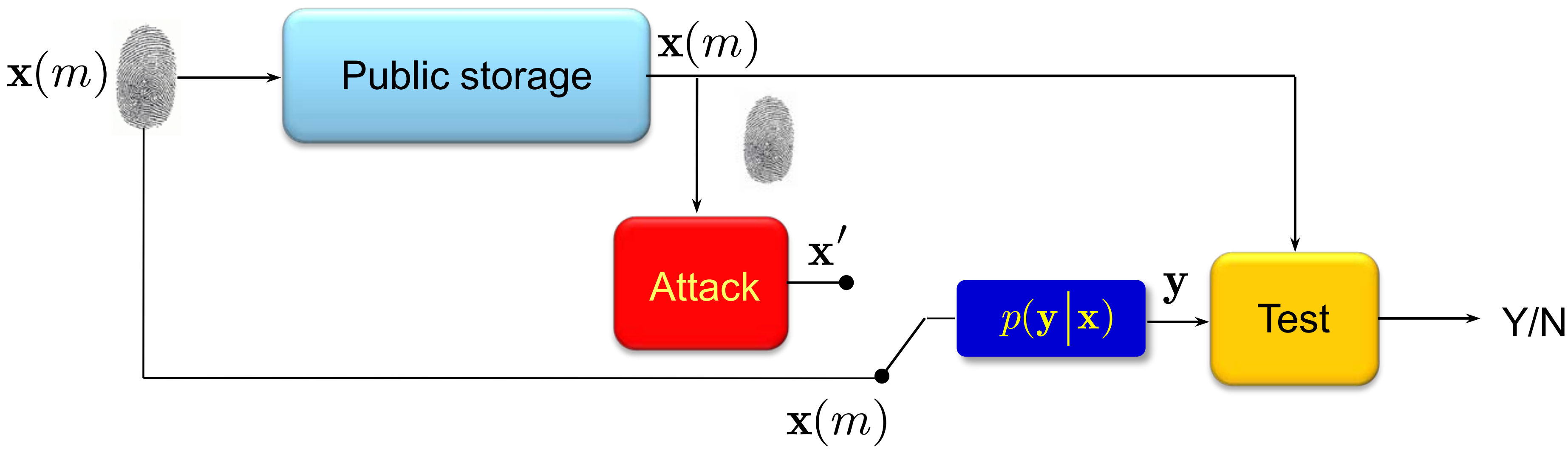
$$\rho = \frac{\mathbf{y}^T \mathbf{x}(m)}{N}$$

$$\boxed{P_{sa} \geq P_f}$$

Conclusion:

- the disclosure of $\mathbf{x}(m)$ is dangerous for the performance (security).

Signal processing approach: authentication



Open issues:

- $\mathbf{x}(m)$ is stored in the public domain
- no security
- no privacy

$\left.\begin{array}{l}\text{no security}\\ \text{no privacy}\end{array}\right\}$ $\mathbf{x}(m)$ can be used for various attacks

Signal processing approach: identification

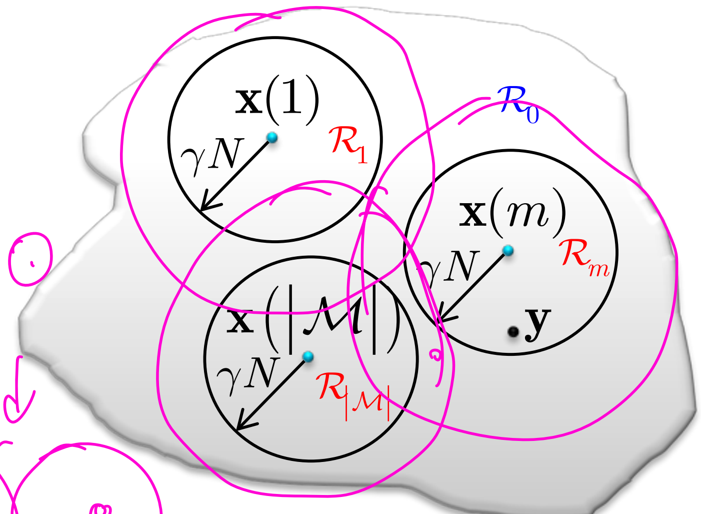
- M-ary hypothesis testing

$$
\begin{cases}
H_0 : \mathbf{y} = \mathbf{x}' + \mathbf{z}, \\
H_1 : \mathbf{y} = \mathbf{x}(1) + \mathbf{z}, \\
\vdots \\
H_{|\mathcal{M}|} : \mathbf{y} = \mathbf{x}\left(|\mathcal{M}|\right) + \mathbf{z},
\end{cases}
$$

$$\mathbf{x}' \neq \mathbf{x}(m), \text{any } 1 \leq m \leq |\mathcal{M}|$$

(a)

(b) $|\mathcal{M}|$



$$\hat{m} = \underset{1 \leq m \leq |\mathcal{M}|}{\arg\min} \left(\left\| \mathbf{y} - \mathbf{x}(m) \right\|^2 \leq \gamma N \right)$$

$\to \hat{m}$

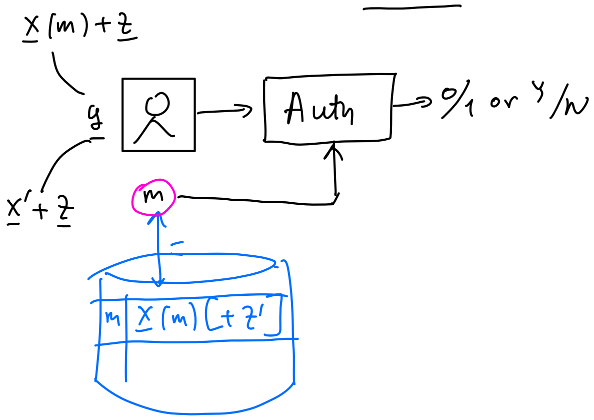
$\to \emptyset$

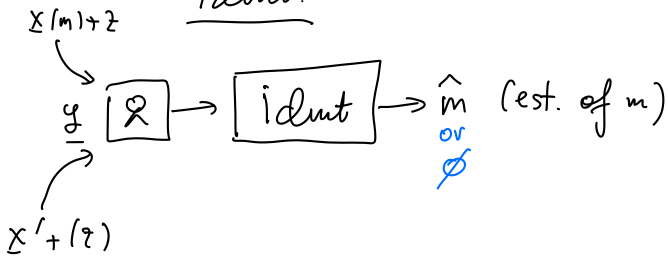
$$P_f = \Pr\left[\bigcup_{m=1}^{|\mathcal{M}|} \mathbf{y}^T \mathbf{x}(m) \geq \gamma' N \middle| H_{0\,\text{blind}} \right]$$

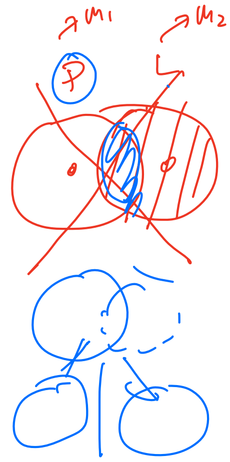
$$P_{sa} = \Pr\left[\bigcup_{m=1}^{|\mathcal{M}|} \mathbf{y}^T \mathbf{x}(m) \geq \gamma' N \middle| H_{0\,\text{informed}} \right]$$

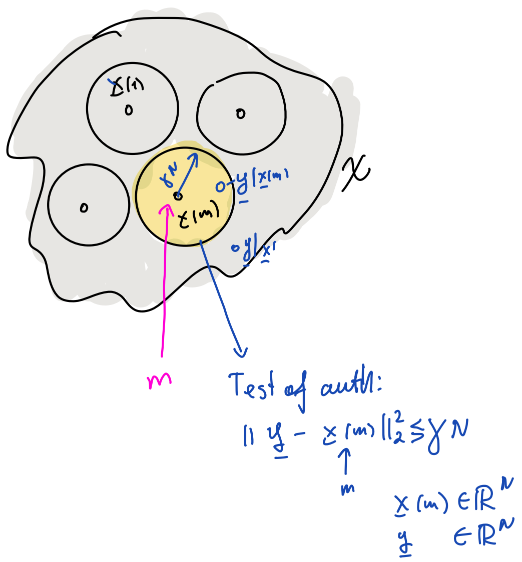
$$P_{ic} = \Pr\left[\underbrace{\mathbf{y}^T \mathbf{x}(m) < \gamma' N}_{\text{miss}} \bigcup \underbrace{\bigcup_{m' \neq m}^{|\mathcal{M}|} \mathbf{y}^T \mathbf{x}(m') \geq \gamma' N}_{\text{missaccaptance}} \middle| H_m \right]$$

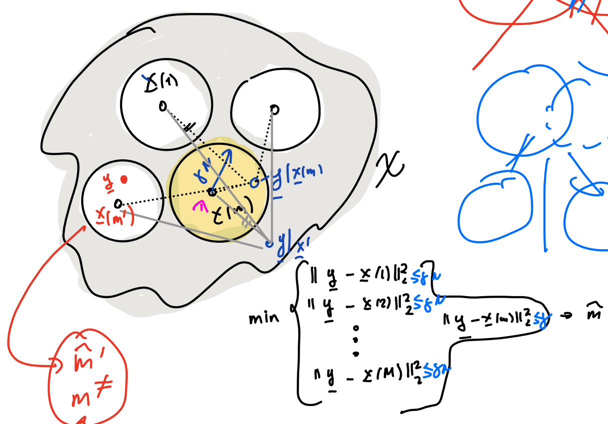
Auth	Ident.



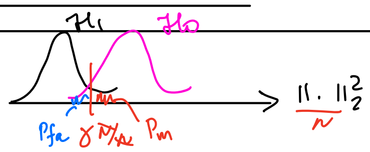




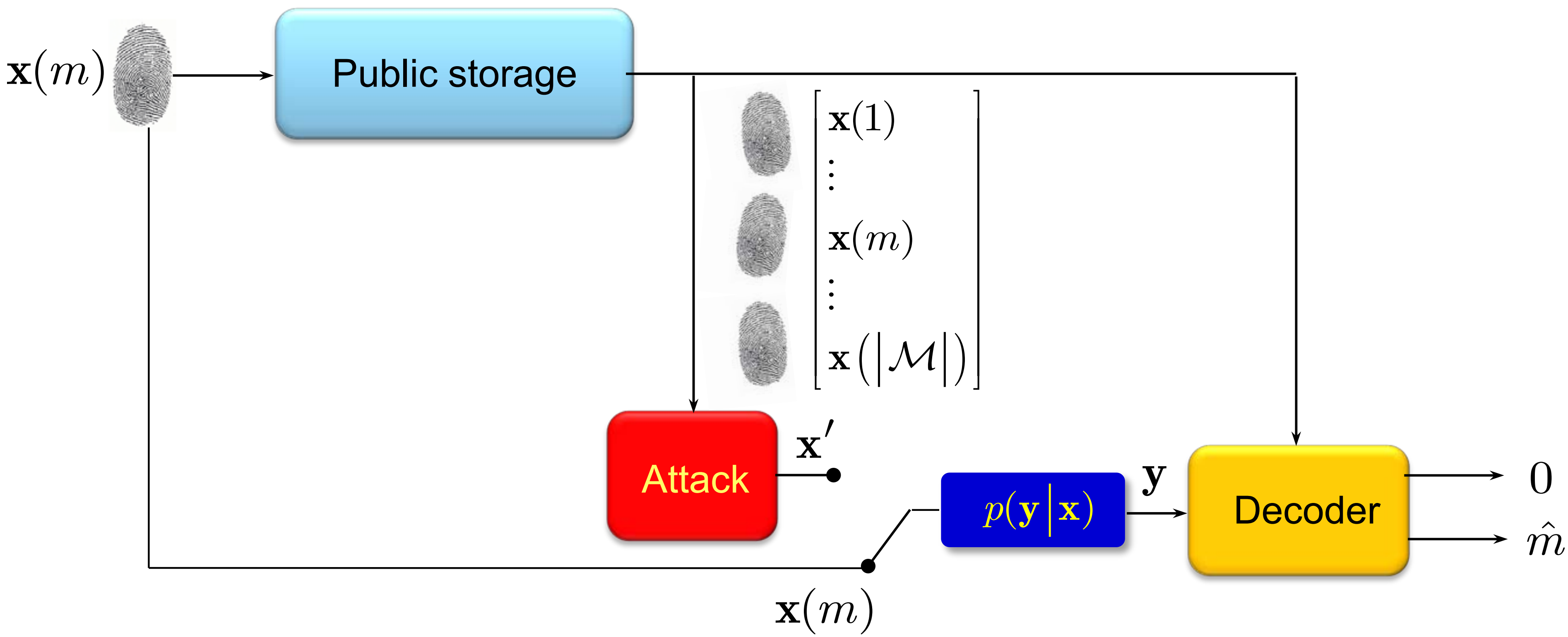




o Conclusions :

	Auth	Ident.
Performance	 $\boxed{P_{fa}(\gamma) \quad P_m(\gamma)}$	$\boxed{(M-1)\cdot P_{fa}(\gamma) \quad P_m(\gamma)}$
Complexity	$O(\text{"1"})$ $\lVert \underline{y} - \underline{x}(m) \rVert_2^2$ one-to-one $\underline{y}$ (vs) $\underline{x}(m)$	$O(\text{"M"}) \sim$ A-NN 'approx one-to-many $\underline{y}$ (vs) $\{\underline{x}(m)\}_{m=1}^{M}$

Signal processing approach: identification



Open issues:

- all $\{\mathbf{x}(m)\}$ are stored in the public domain
- no security
- no privacy

$\left.\begin{array}{l}\text{no security}\\ \text{no privacy}\end{array}\right\}$ $\mathbf{x}(m)$ can be used for various attacks

$x(m)$ H W f_ϕ $b_x(m)$

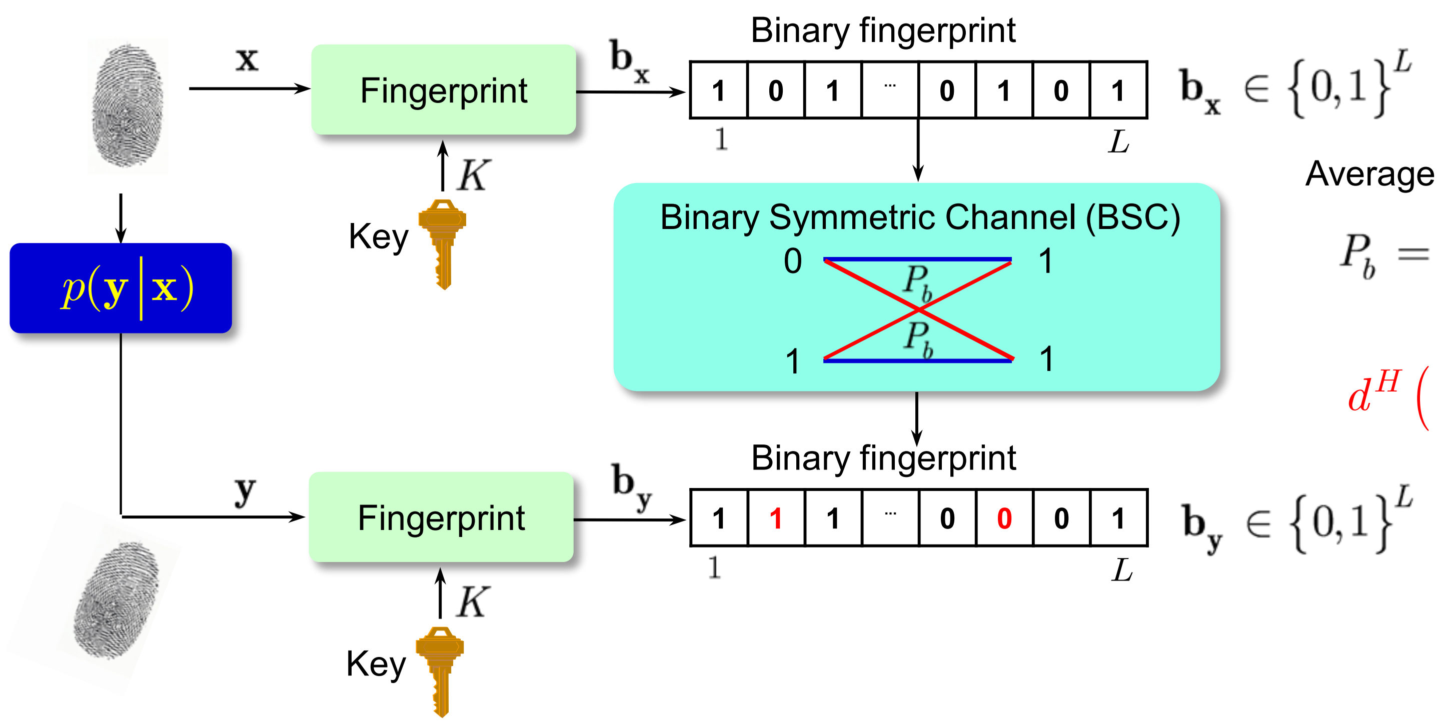
ML < AE, Classif, SSL (see lecture 1).

HC: $\sigma(W x(m))$ (see lecture on robust perc. hashing).

Signal processing approach: towards «robust hashing»

what for: (a) complexity (↓). ($O(HW)$ real vs $O(L)$ binary).
(b) privacy.

- If $\mathbf{x}(m)$ is open, the attacker can: (a) deduce privacy and (b) design attacks
- Robust hashing: an attempt to mimic crypto hashing but stay robust to signal processing (blur, noise, lossy compression, etc.) and geometric (affine, projective) distortions.



Average probability of bit error

$$P_b = \frac{1}{L}\sum_{i=1}^{L} \Pr\left[b_{x_i} \neq b_{y_i}\right]$$

$$d^H\left(\mathbf{b}_\mathbf{x}(m), \mathbf{b}_\mathbf{y}\right) \leq \alpha L$$

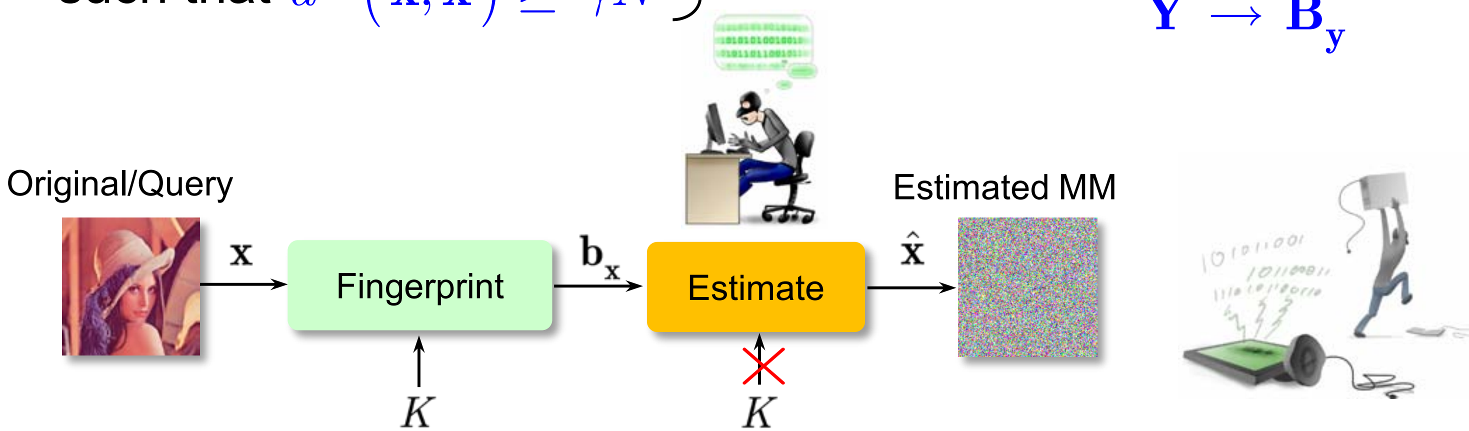
Signal processing approach: towards «robust hashing»

- Main assumptions:
  - Robust hashing is robust to some minor modifications
  - Robust hashing is non-invertible under
    - (a) unknown key
    - (b) known key

      such that $d^E\left(\mathbf{x}, \hat{\mathbf{x}}\right) \geq \gamma N$

This is possible due to loss of information

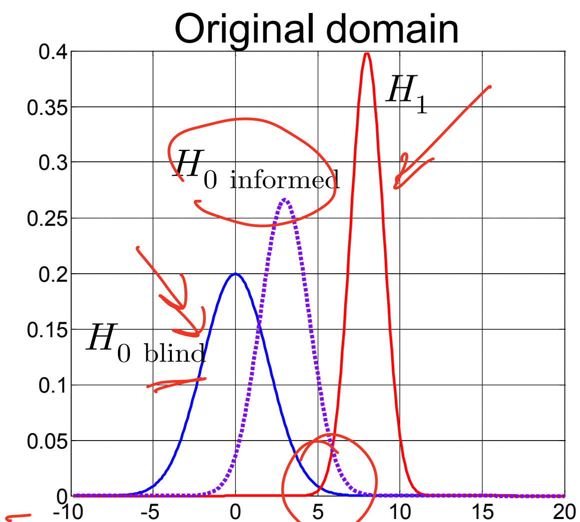
$$\mathbf{X} \rightarrow \mathbf{B_x}$$
$$\mathbf{Y} \rightarrow \mathbf{B_y}$$



Remark: authentication/identification based on $\left(\mathbf{B_x}, \mathbf{B_y}\right)$ is less accurate than based on $\left(\mathbf{X}, \mathbf{Y}\right)$

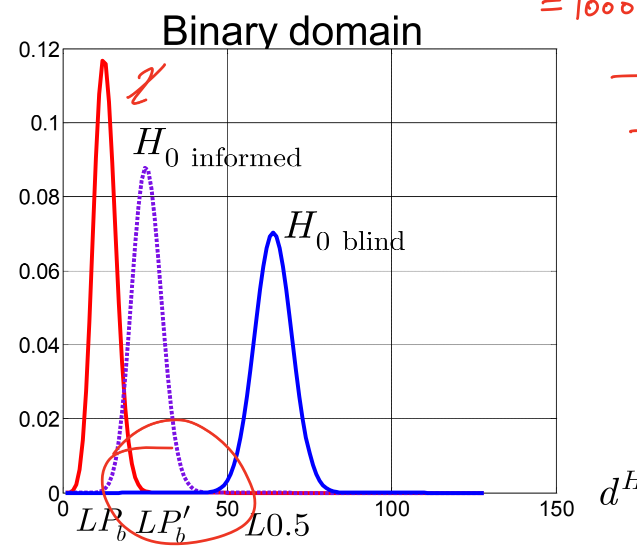
Signal processing approach: towards «robust hashing»

- Impact of reduction of dimensionality and binarization:
  - FP: $\mathcal{R}^N \times \mathcal{K} \rightarrow \{0,1\}^L$



Fingerprinting

Loss of information



$$\rho = \frac{\mathbf{y}^T \mathbf{x}(m)}{N}$$

max

$\min \left[\frac{1}{N} \| y - x(m) \|_2^2 \right]$

$\|y\|^2 - 2y^T x(m) + \|x(m)\|_2^2$

$d^H(b_y, b_{x(m)})$

L = 128 → ✓ → privacy

= 1000

L=128

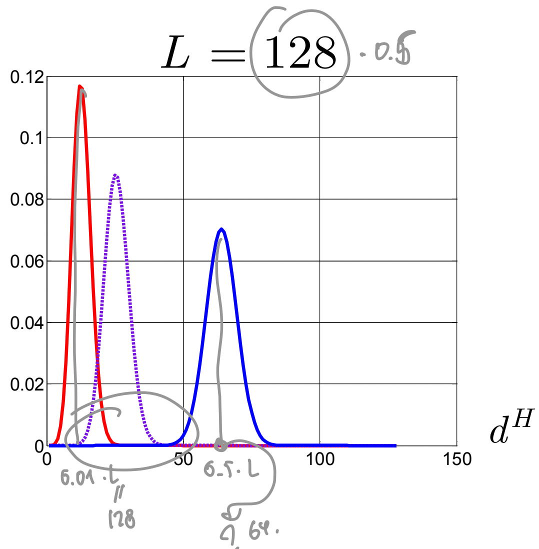
L=1000

Hybrid solution

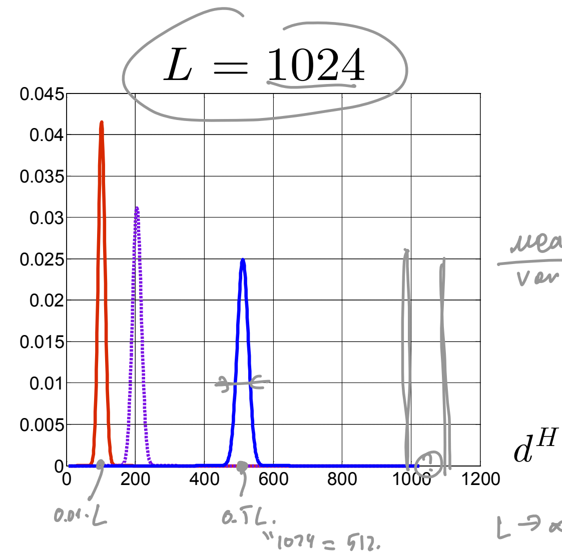
$\underline{x}(m) \rightarrow b_x(m) \rightarrow$; $\underline{y} \rightarrow b_y$; P_b : $\mathcal{H}_1$ (orig.): $P_b \rightarrow 0.01$; $\mathcal{H}_0$ (fake): $P_b \rightarrow 0.5$

$\mathcal{B}(L, P_b)$ M: $L \cdot P_b$ V: $L \cdot P_b(1-P_b)$

- Application of non-invertible transformations leads to the loss in performance
- One can compensate it by selecting longer L



Increase L $\Rightarrow$



$\frac{\text{mean}}{\text{var.}} = \sqrt{\frac{L}{\sigma^2}}$; $L \rightarrow \infty$

- In turn, longer L leads to better chances for image reconstruction!
- Problem: can one trade-off security/privacy – performance?

$\Rightarrow$ Solution: crypto + signal processing + coding

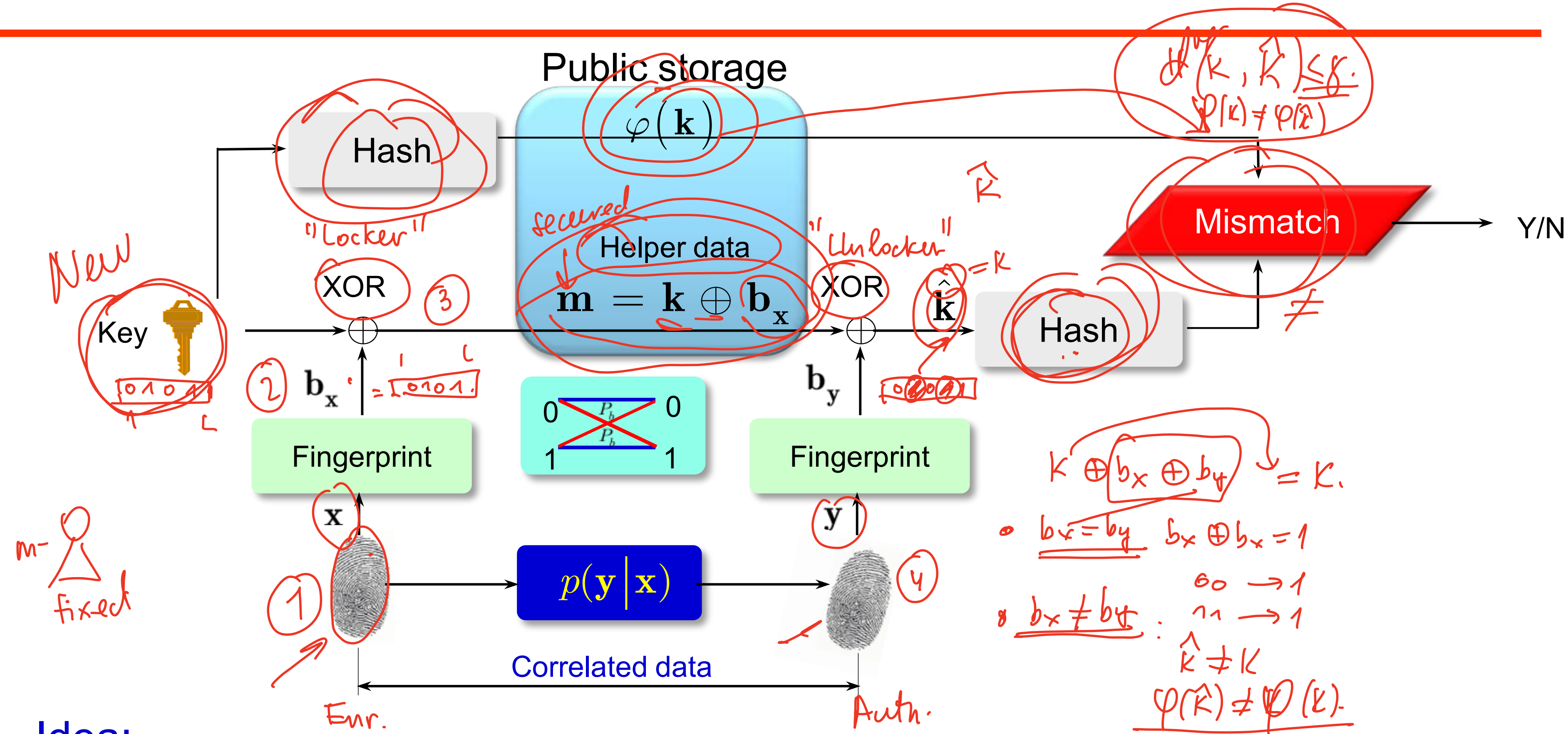
B. Scovič

Hybrid solution: strategies

- Several methods (based on common idea):
  - fuzzy commitment
  - helper data

- Main strategy:
  - use additional helper data to correct errors
  - use a fact that $\mathbf{X}$ and $\mathbf{Y}$ are correlated as well as $\mathbf{B_x}$ and $\mathbf{B_y}$ for the hypothesis H_1 in authentication and the hypothesis H_m in identification

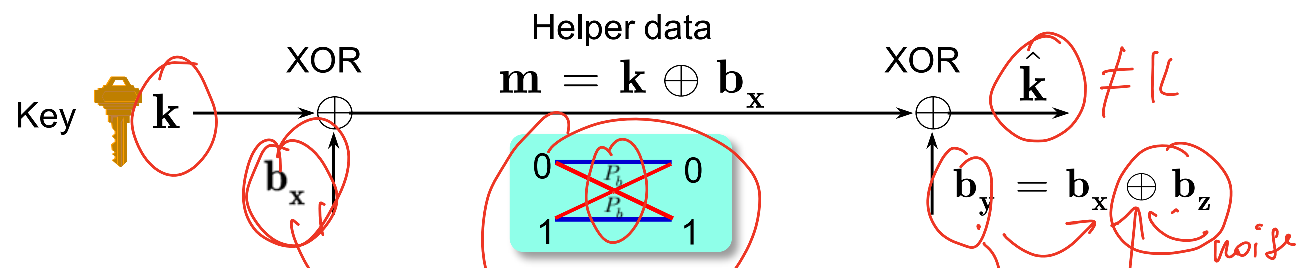
Hybrid solution: fuzzy commitment



- Idea:
  - $\mathbf{k}$ is used for every new session (i.i.d.) while $\mathbf{b}_\mathbf{x}$ remains the same (non-renewable)
  - $\mathbf{b}_\mathbf{x}$ is used to lock the key (even, if it is not i.i.d.) $\Rightarrow$ analog of one-time-pad

Hybrid solution: fuzzy commitment

- Open issues:



$P_b = 0.01$

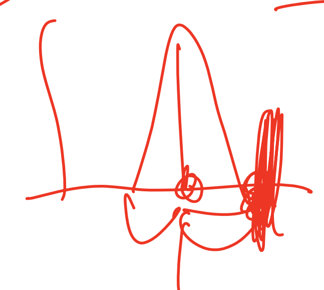
$L = \sim L o P_b$

$XOR = "+"$.

- In general case,
  - $\mathbf{b_x} \neq \mathbf{b_y} \Rightarrow$ residual error

$$\hat{\mathbf{k}} = \underbrace{\mathbf{k} \oplus \mathbf{b_x}}_{m} \oplus \mathbf{b_y} = \mathbf{k} \oplus \mathbf{b_z} \Rightarrow \varphi(\mathbf{k}) \neq \varphi(\hat{\mathbf{k}})$$

$\underbrace{\mathbf{b_x} \oplus \mathbf{b_y}}_{\mathbf{b_z}}$



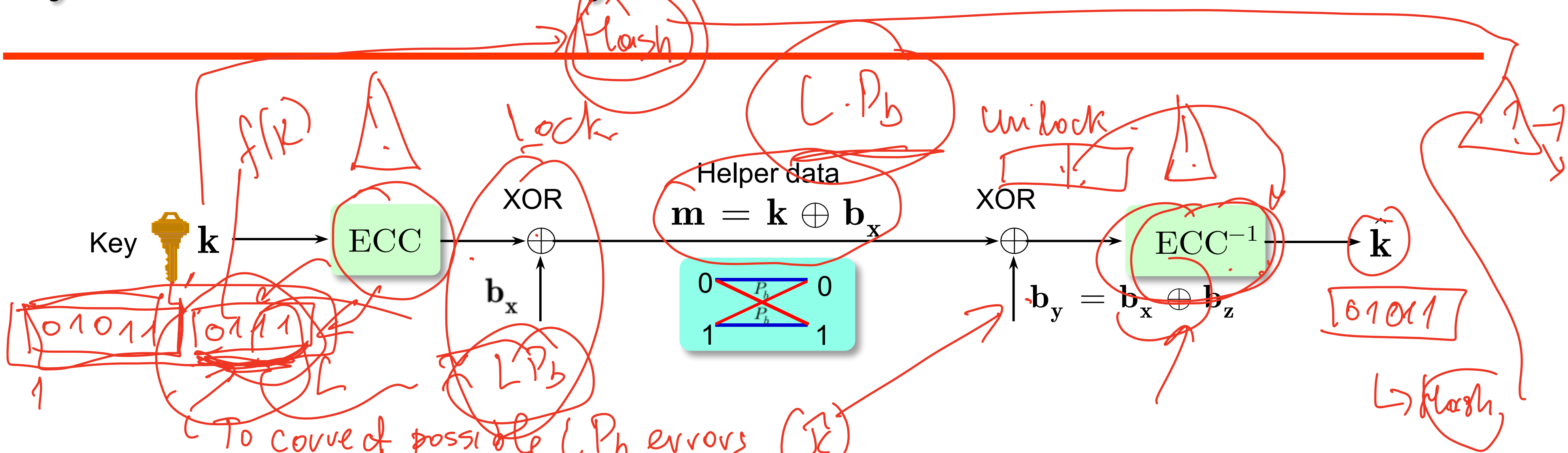
$\sqrt{Var}$

$LP_b + 3\sqrt{LP_b(1-P)}$

$\mu + 3\sigma$.

- Idea:
  - add redundancy to $\mathbf{k}$ using error correction code to correct errors
  - redundancy is proportional to $\approx LH_2(P_b)$

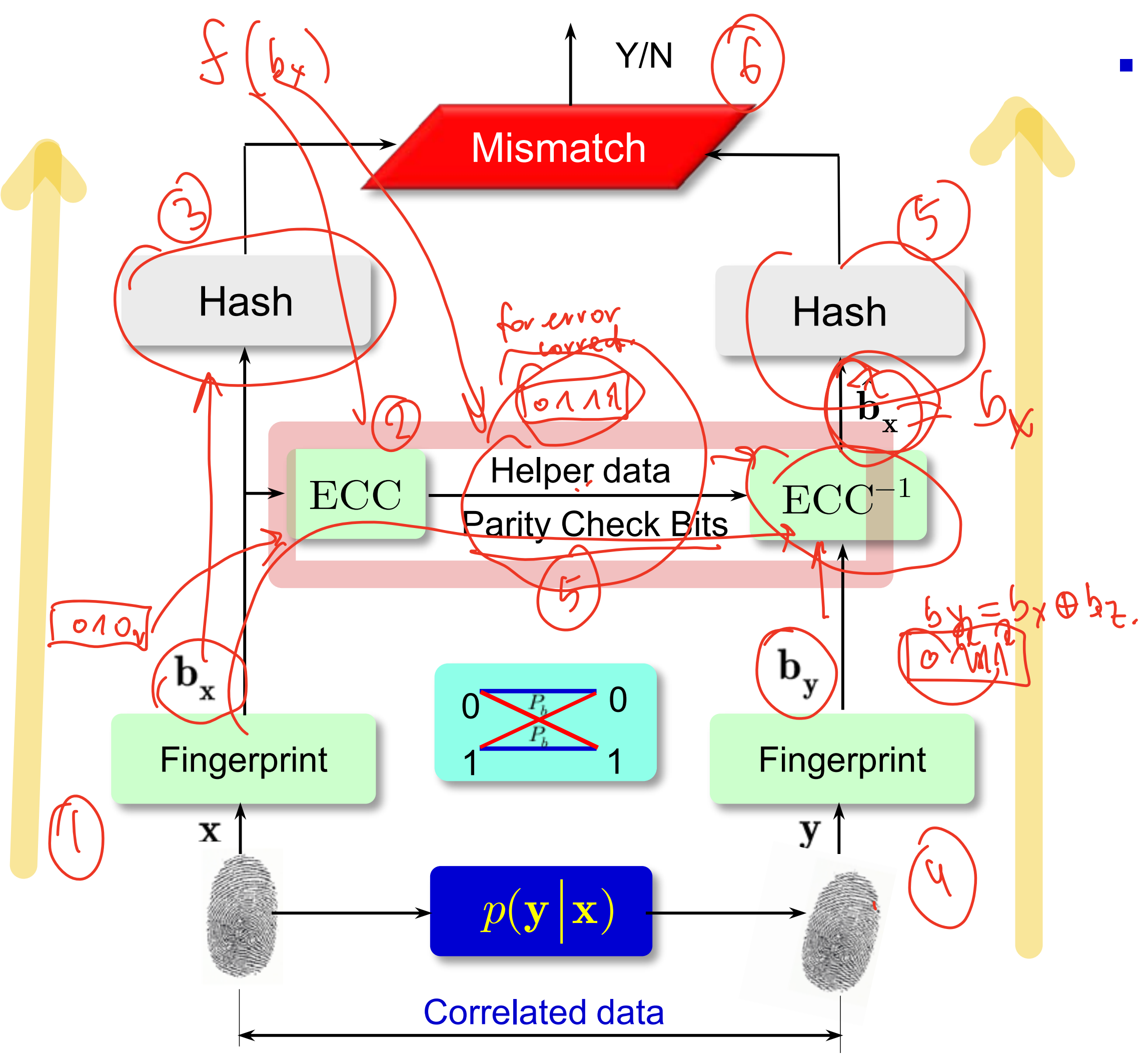
Hybrid solution: fuzzy commitment



- ECC^{-1} decoder corrects errors in $\mathbf{k} \oplus \mathbf{b_z}$

- Open issues:
  - $\mathrm{ECC}(\mathbf{k})$ is not anymore i.i.d.
    - $\Rightarrow$ smaller entropy: easier to predict and attack
  - In addition $\mathbf{b_x}$ is not i.i.d., the attacks are possible against both!

Hybrid solution: helper data based systems



- Open issues:
  - redundancy is proportional to $\approx LH_2(P_b)$
  - However, these methods represent the state-of-the-art!
  - It is up to you to find something better.