Side-Channel Attacks Against the Human Brain: the PIN Code Case Study

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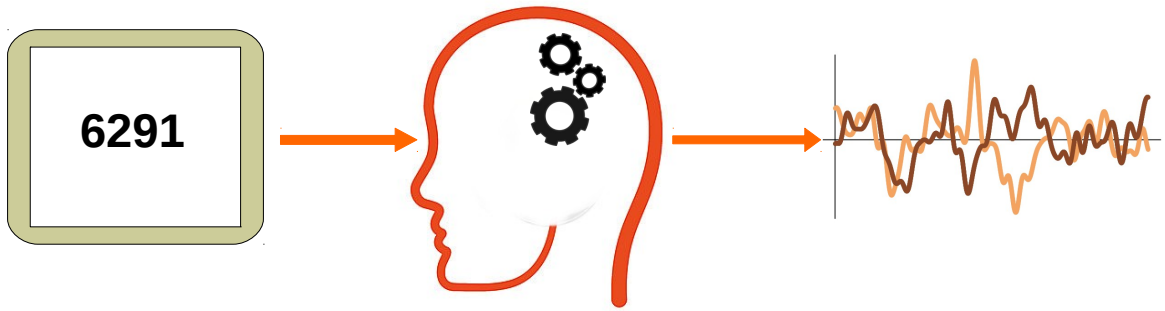
Cosade 2017, Paris, France

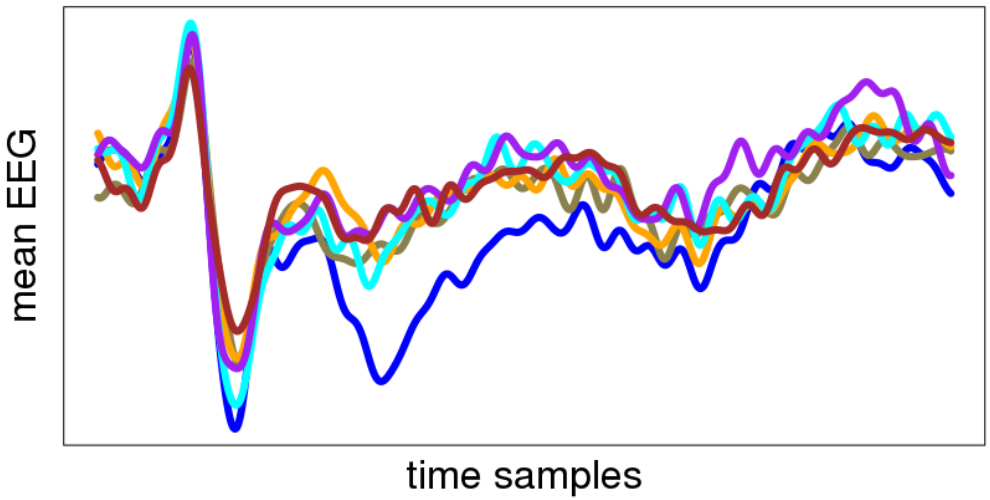
Introduction

- Side-channel attacks allow PIN code recoveries
  - e.g., Le Bouder et al., *A Template Attack against Verify PIN Algorithms*, SECRYPT 2016
- Can we apply them to BCIs & EEG signals?



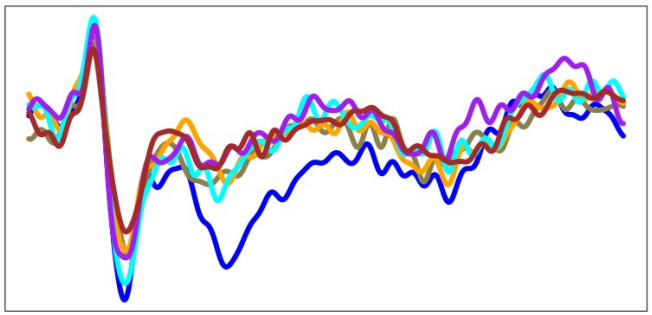
Motivation

- Feasibility shown by Martinovic et al. (USENIX 2012)
  - i.e., there is exploitable information in EEG signals



- BCIs more and more commercialized (e.g., for gaming)

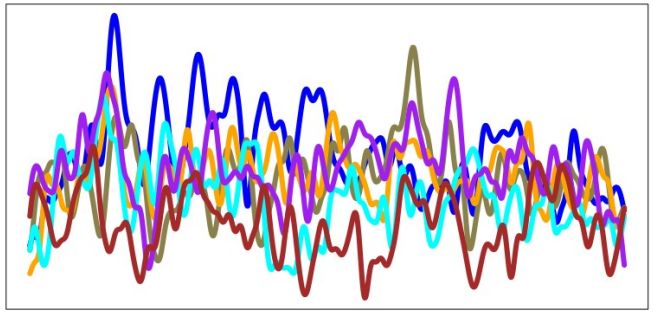
Challenge: low (& irregular) SNR



Range of the
Standard Deviation

≈

Differences in the
mean traces

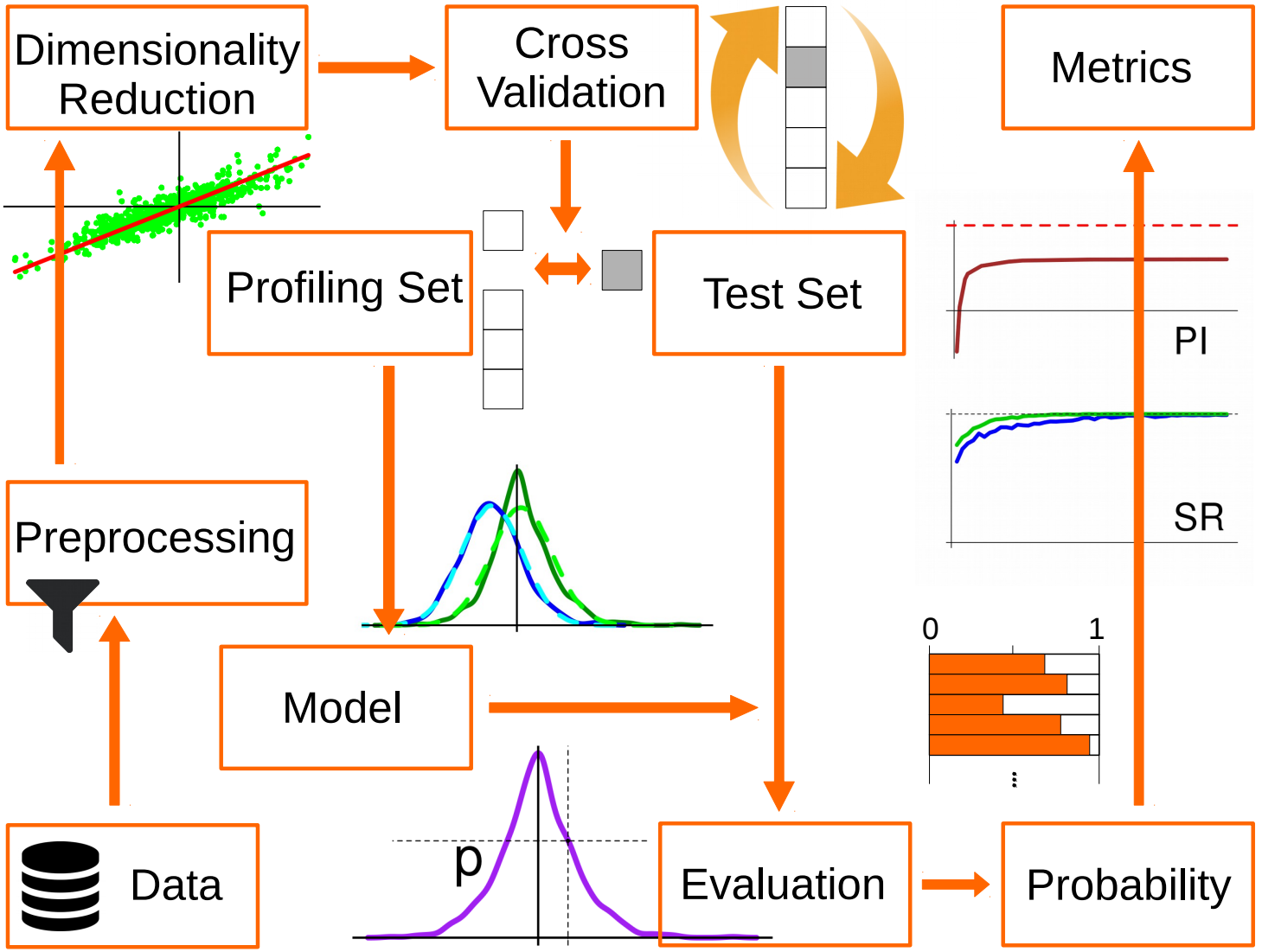


Main questions

- Can we extract PINs exactly (or only partially)?
- Can we extract them with sufficient confidence?
- How do supervised (aka profiled) and unsupervised (aka non-profiled) attacks compare?
- *How similar/different are different subjects?*
- *What are the consequences for security & privacy?*

Note: results can be viewed as positive or negative!

Related works: semantic associations and incongruities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Cross Validation
Metrics
Profiling Set
Test Set
PI
SR
Preprocessing
Model
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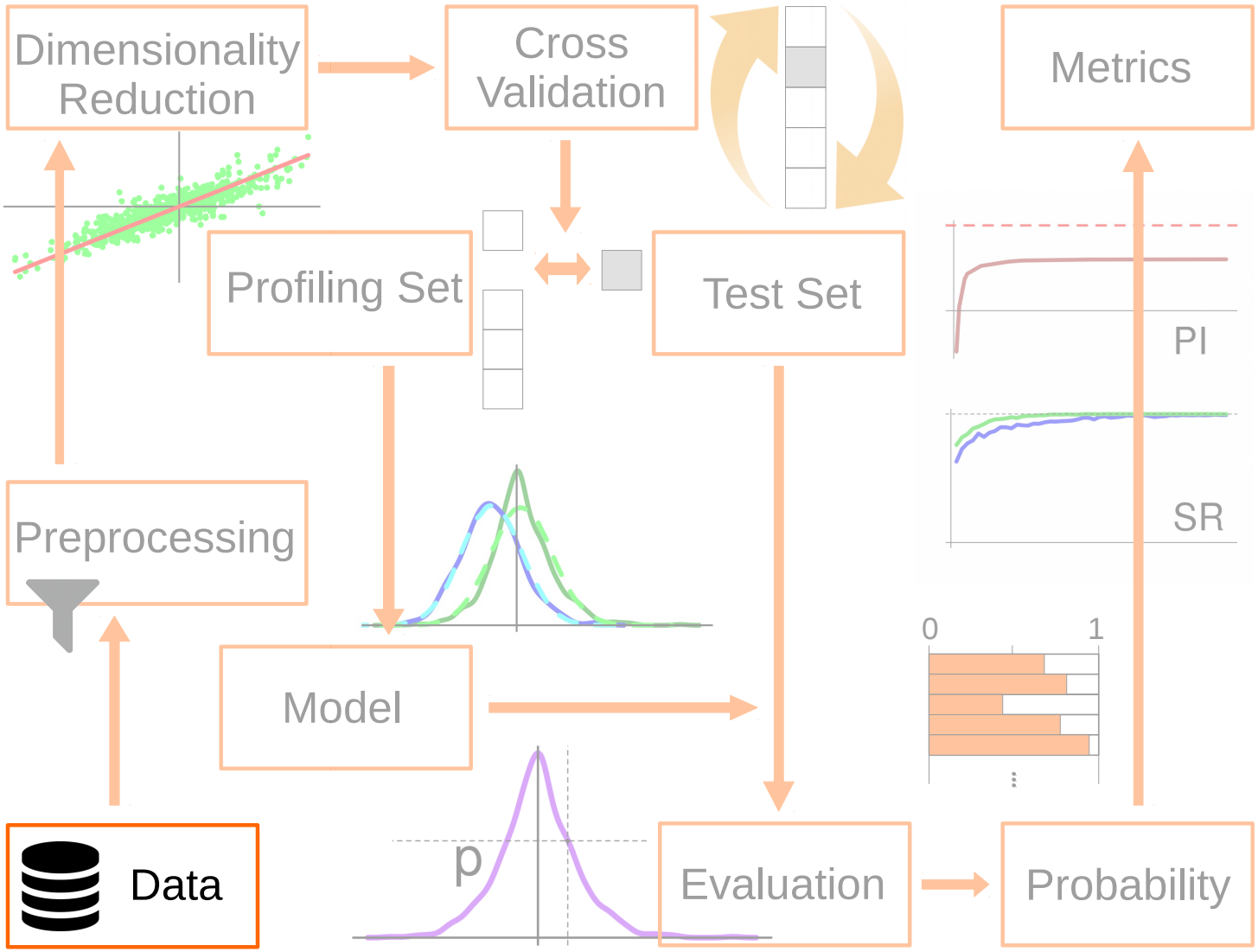
Data
Evaluation
Probability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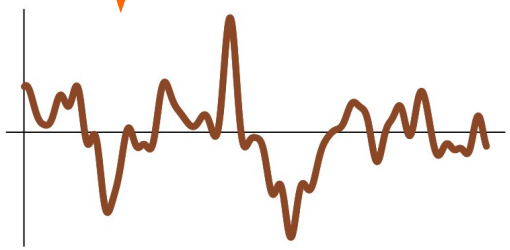
The data

8 subjects

pins

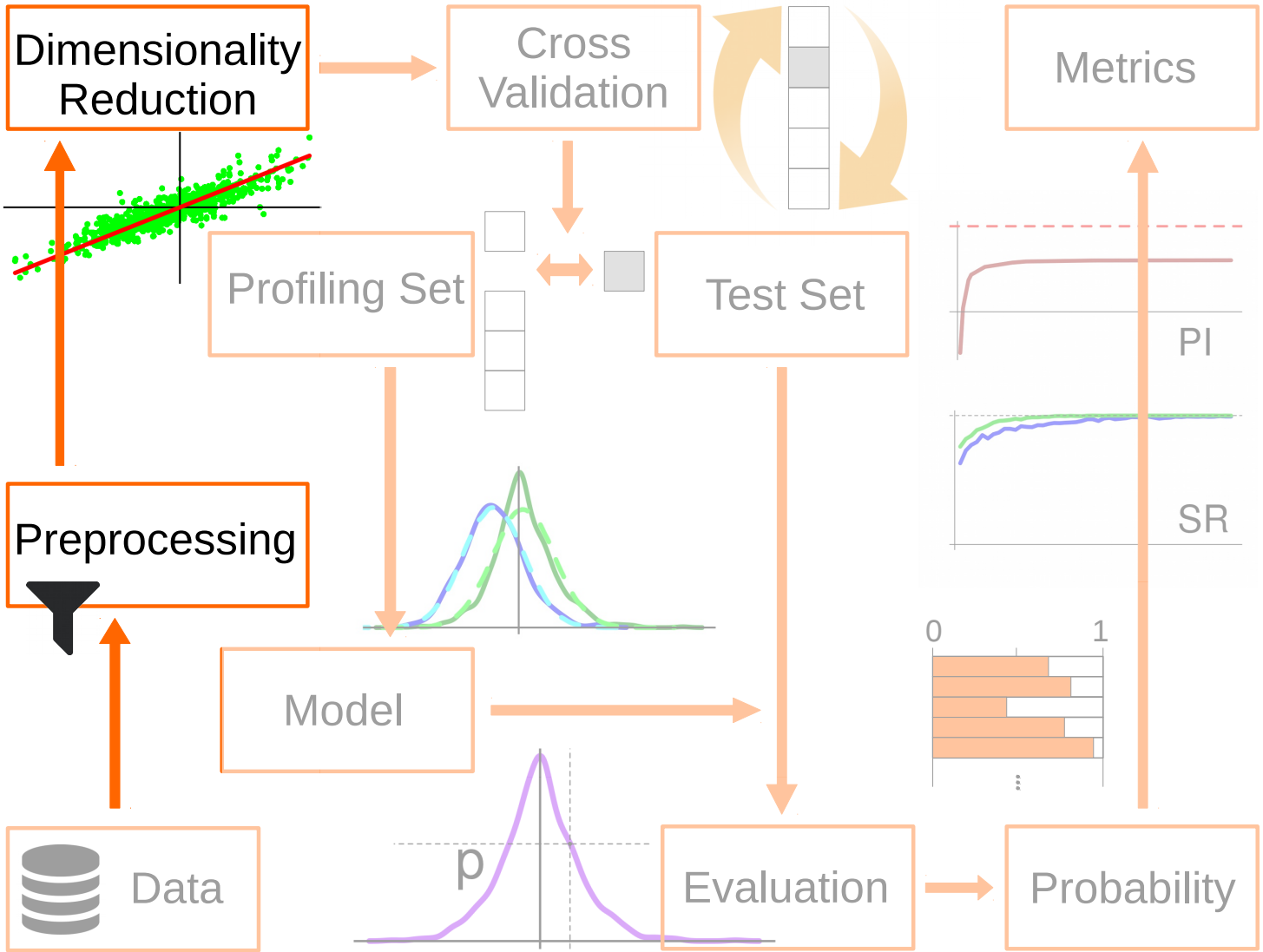
Headset :
32 electrodes



1000 x 1 ms

150 traces

- per pin
- per subject
- per electrode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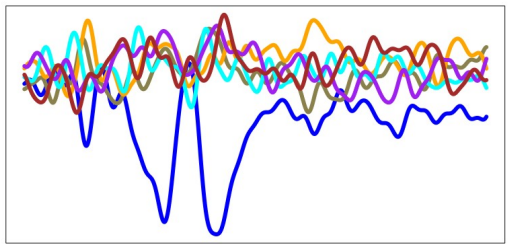
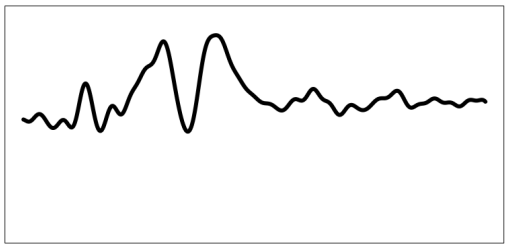
Dimensionality reduction

Principal Component Analysis (PCA)

Mean traces

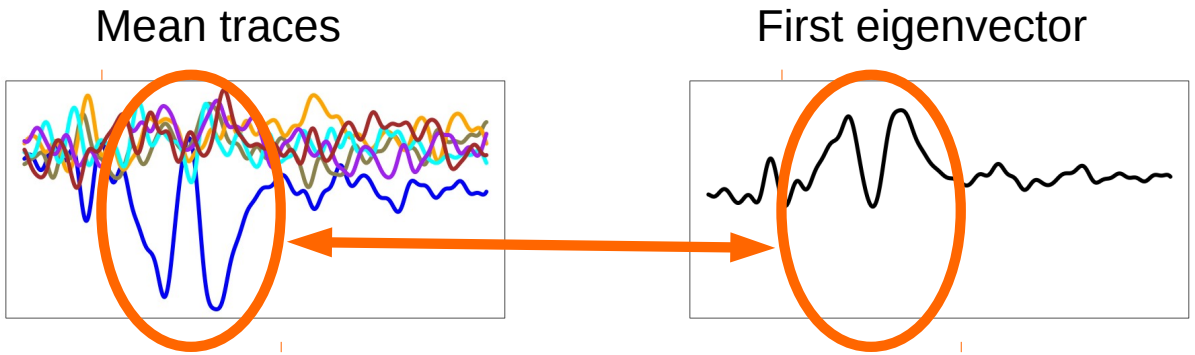


First eigenvector



Dimensionality reduction

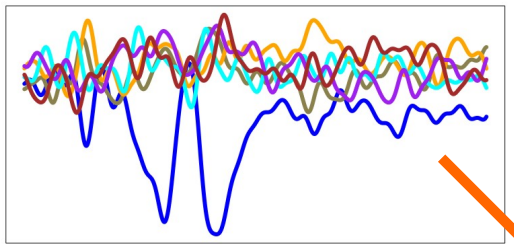
Principal Component Analysis (PCA)



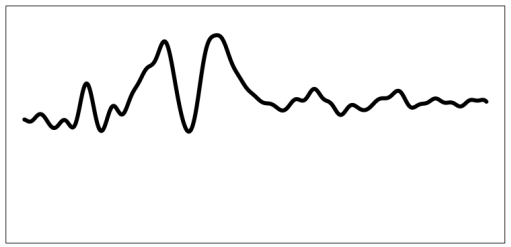
Dimensionality reduction

Principal Component Analysis (PCA)

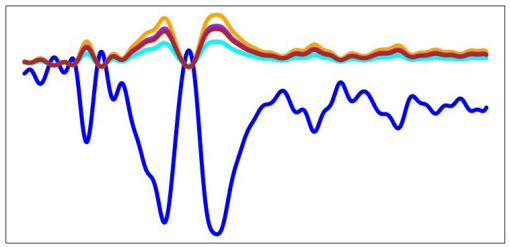
Mean traces



First eigenvector

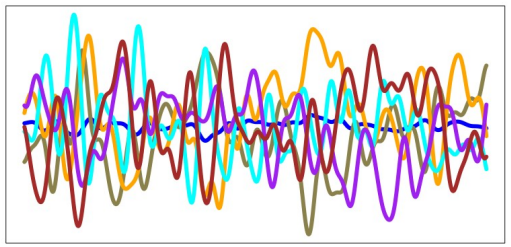


Reconstructed signal (1D)



+

Reconstructed signal (other Ds)

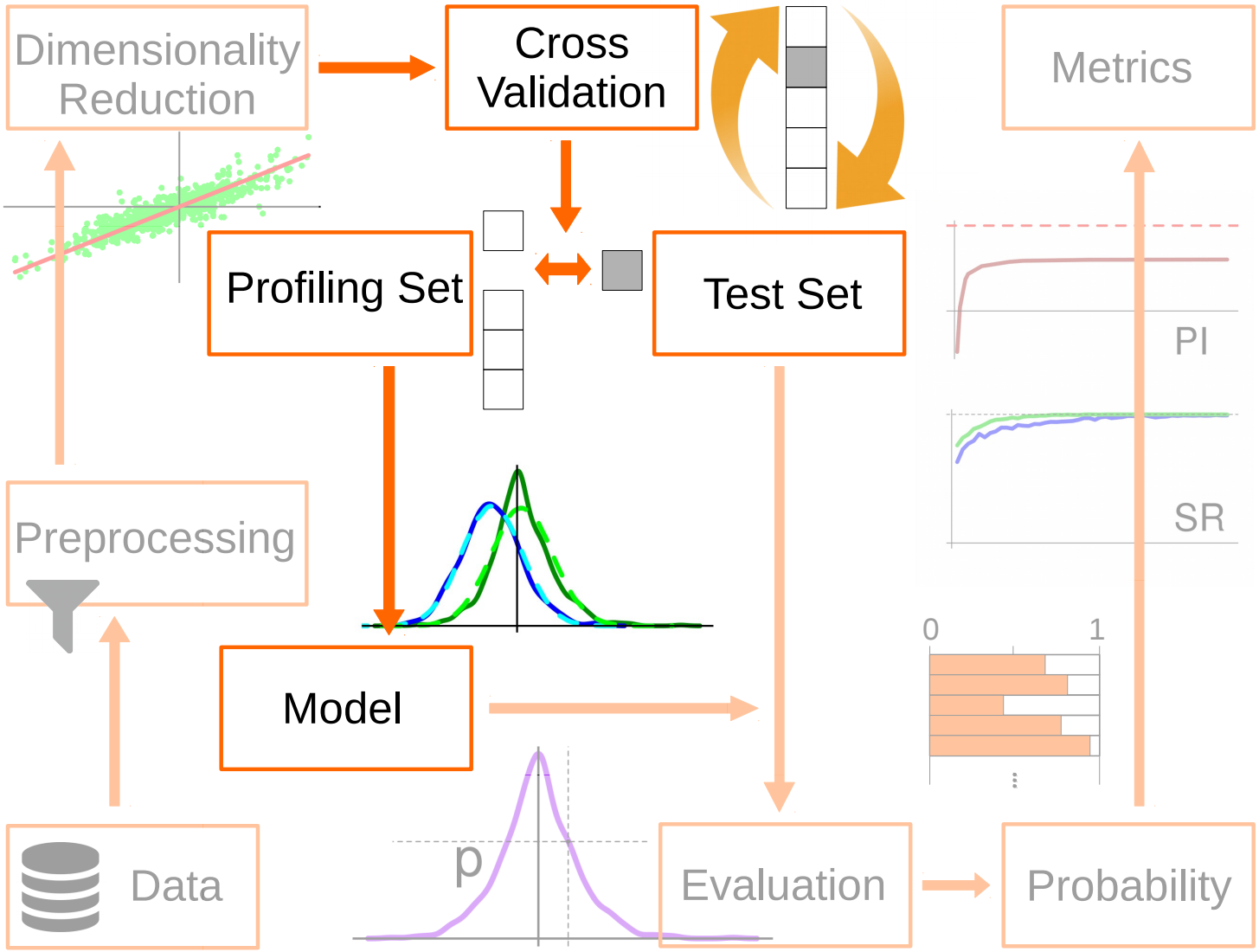


Principal Component Analysis

\+ Average PCA: one dimension is sufficient
\+ Projects 1000 dimensions to a single one

– Estimating means becomes expensive with many PINs

$\Rightarrow$ Raw PCA also studied in the paper
(Requires more dimensions and outliers management)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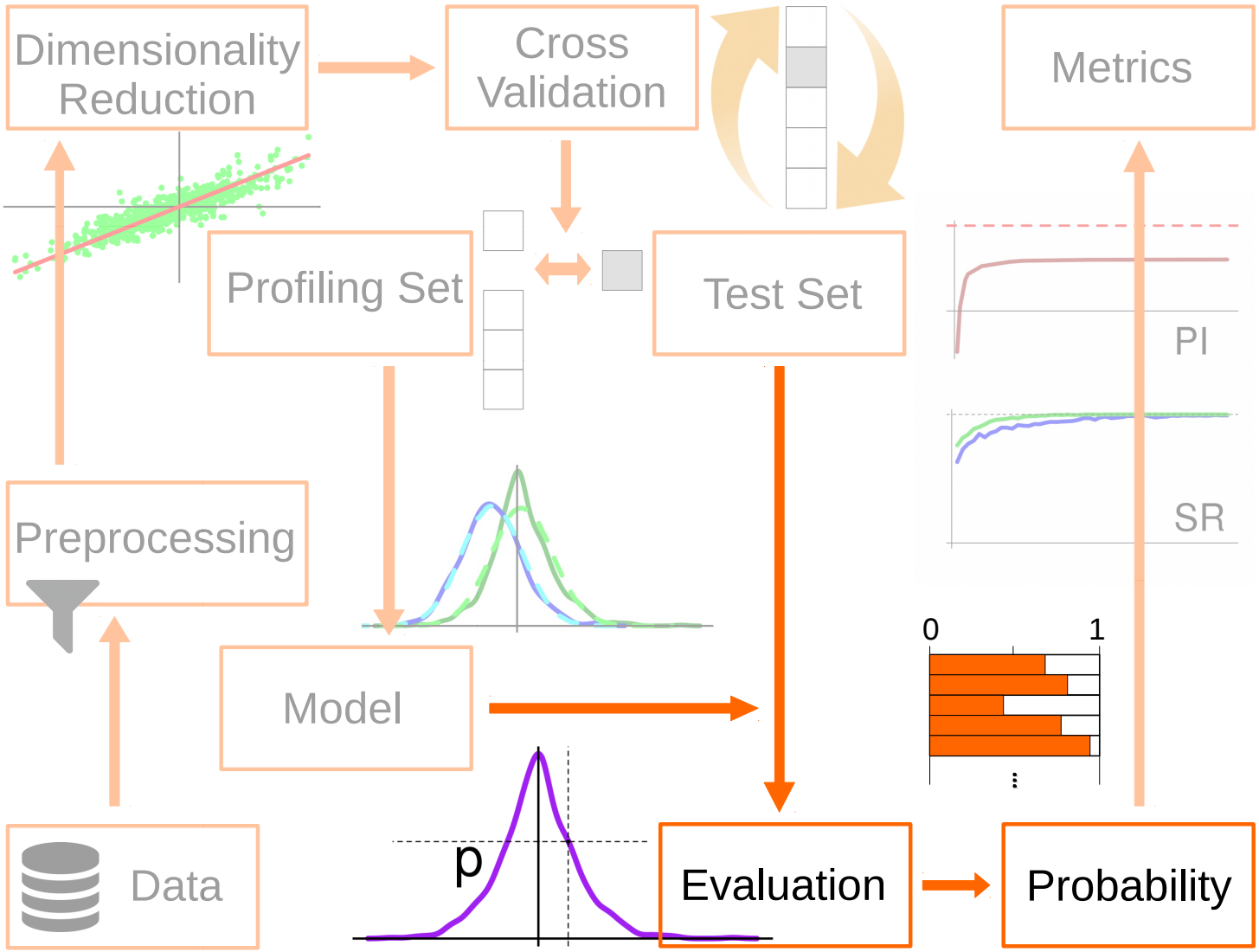
Profiling/modeling

- **Gaussian** estimation with mean $\hat{\mu}$ and variance $\hat{\sigma}$:

$$\hat{f}_{\mathrm{g}}(x) = \frac{1}{\sqrt{2\pi\hat{\sigma}}} \exp\left(-\frac{1}{2}\left(\frac{x-\hat{\mu}}{\hat{\sigma}}\right)^2\right)$$

- **Kernel** density estimation with bandwidth parameter h and samples $x_1, \ldots, x_n$:

$$\hat{f}_{\mathrm{k}}(x) = \frac{1}{nh}\sum_{i=1}^{n} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-x_i}{h}\right)^2\right)$$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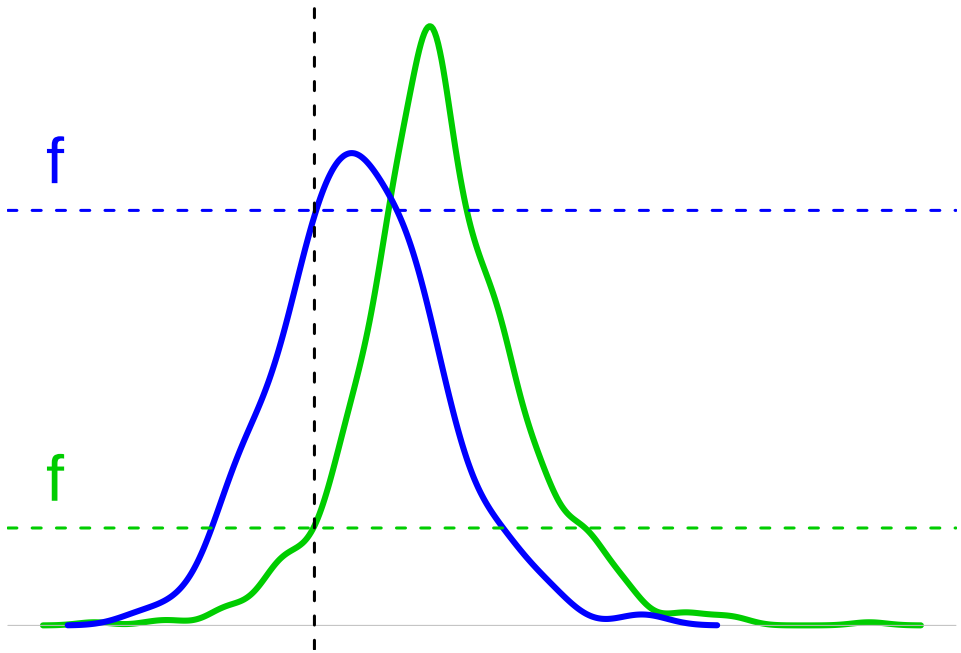
Model evaluation



Probability generation

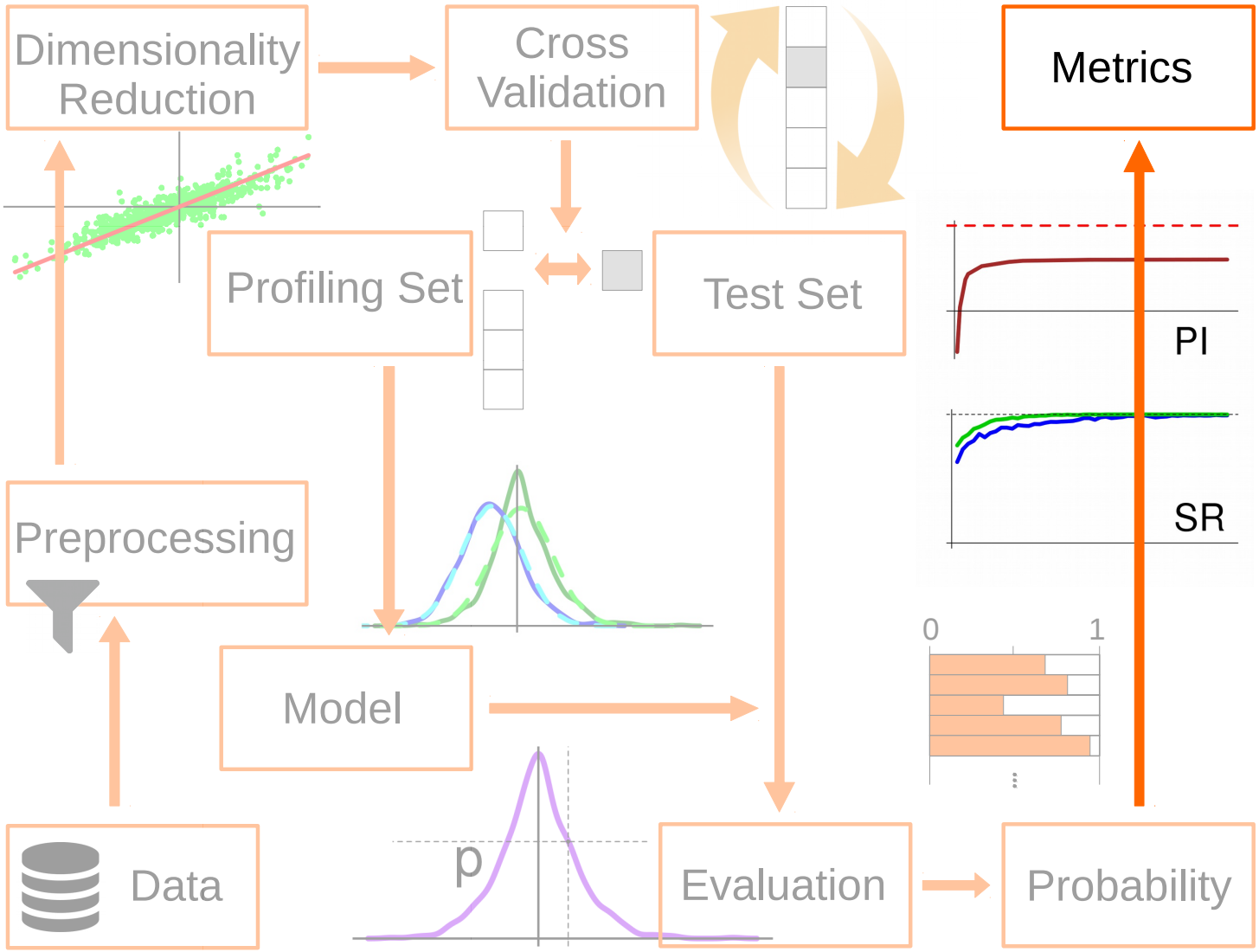
- From the estimated PDFs

$$\hat{\mathbf{f}}_{model}[\mathbf{o} \mid \mathbf{p} = \text{correct PIN}] = f,$$

$$\hat{\mathbf{f}}_{model}[\mathbf{o} \mid \mathbf{p} = \text{incorrect PIN}] = f.$$

- Produce probabilities thanks to Bayes

$$\hat{\mathbf{Pr}}_{model}[\mathbf{p} \mid \mathbf{o}] = \frac{\hat{\mathbf{f}}_{model}[\mathbf{o} \mid \mathbf{p}] \cdot \mathbf{Pr}[\mathbf{p}]}{\sum_{p^\star} \hat{\mathbf{f}}_{model}[\mathbf{o} \mid \mathbf{p}^\star] \cdot \mathbf{Pr}[\mathbf{p}^\star]}$$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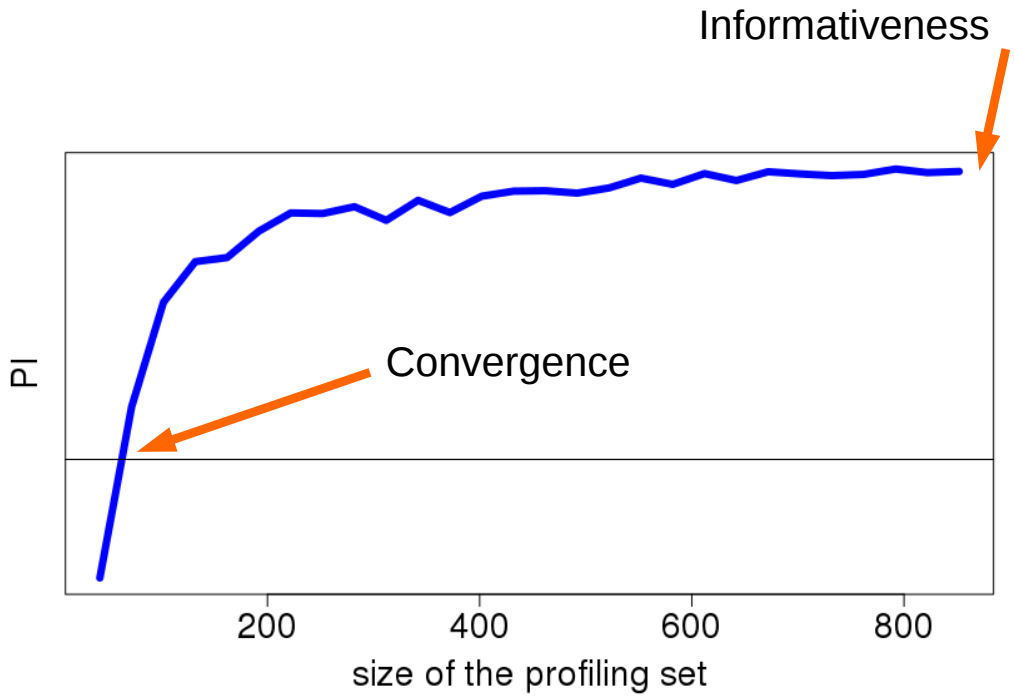
Metrics

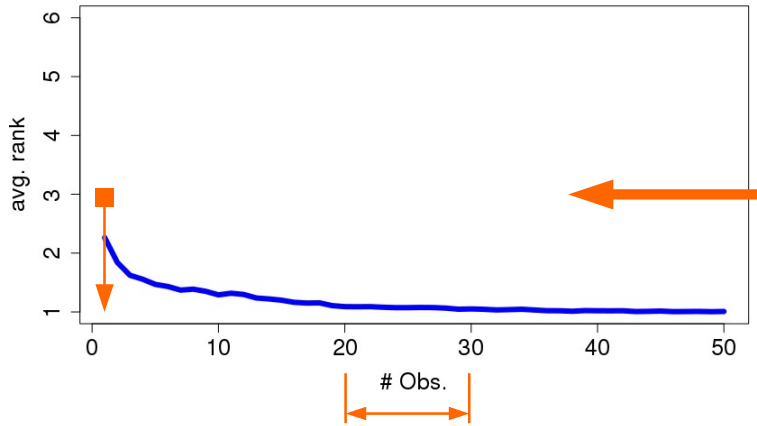
- **Perceived Information (PI)**: amount of information extracted from the observations (given a model)
- **Success Rate**: probability of correct classification (estimated for correct and incorrect PIN values)
- **Average rank**: average position of the correct PIN value in the sorted list of 6 possible ones

Profiled attacks: PI



- Convergence reached after $\approx$ 200 to 400 traces

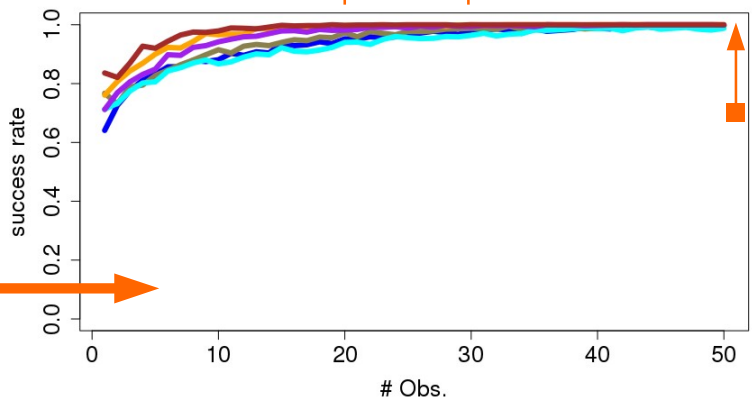
Profiled attacks: SR & avg. rank



Rank 3 to 1

Need about 20-30 traces

Success Rate from
65-85% to 100%



Profiled attacks: summary

- PIN recovery for most subjects (7 out of 8)
  - Failure due to another "distinguishable" event
  - Seems inherent to the investigated setup

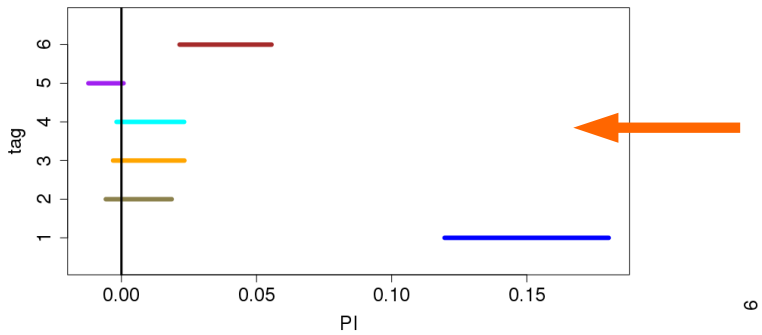
$\Rightarrow$ We minimized false negatives (to allow enumeration)

- Answers our first questions: PINs can be extracted from EEG signals partially and with good confidence
  - $\exists$ scenarii where this can be damaging
- Profiling more expensive than online attack
  - Given a good model is available

Unprofiled attacks

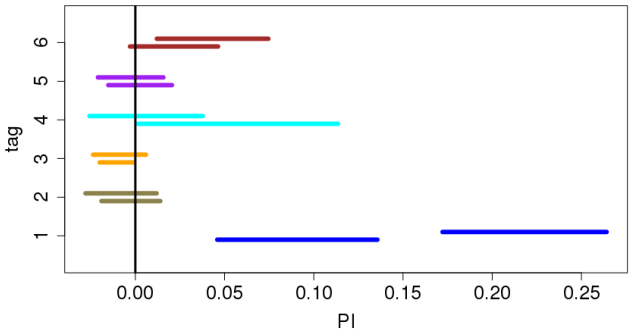
- Consider each PIN to be the correct one
- Estimate the PI on-the-fly for each case
  - And compute confidence intervals
- Correct PIN is expected to have the highest PI

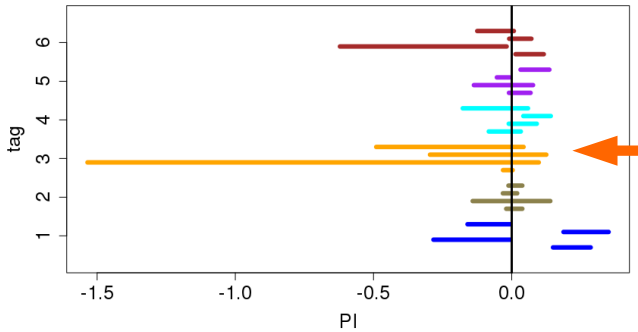
Unprofiled attacks: results



≈ 1 x 900

≈ 2 x 450





≈ 4 x 225

- Nicely correlated with the profiling cost (slide 21)

Other results

- **Portability**: attack one subject with a model built from others' data: less successful (5 out of 8)
- **Privacy**: target the subjects' identities instead of their PIN: positive results obtained for all users

Conclusions

- Information available and exploitable with confidence
- Yet not sufficient for full (4-digit) PIN recovery
- Mostly because of signal instability / subjects' focus
- Biggest risk here: reduction of the guessing entropy

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- Yet not sufficient for full (4-digit) PIN recovery
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- Biggest risk here: reduction of the guessing entropy

More generally...

- Targets of smaller cardinality would be more worrying
- Privacy is also more worrying (unbounded data)
- Motivation for MPC, FHE, ...
- Much more research needed

Thanks !