Double Strike: Breaking Approximation-Based Side-Channel Countermeasures for DNNs

SemSecuElec Seminar

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Agenda

1. Background
2. Methodology
3. Results
4. Conclusions

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Deep Neural Networks (DNNs)

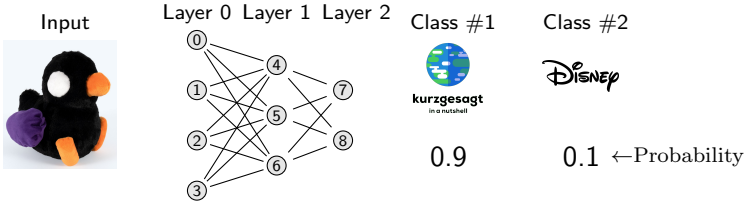
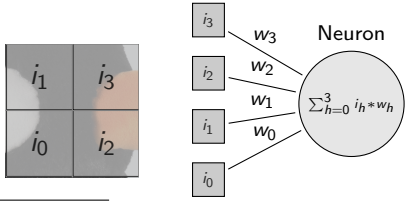


Figure: A DNN brand classifier[1].



[1]Duck and Kurzgesagt Logo belong to Kurzgesagt

The *Weight*(s) of an Economic Damage

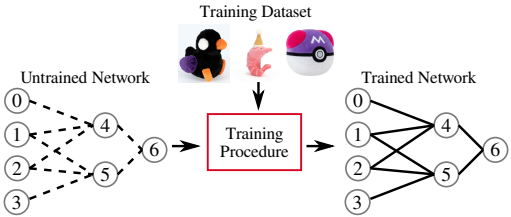


Figure: The training process.[2]

DNN Training is Expensive

- Expensive hardware (e.g., GPUs), time-intensive (e.g., days)

Weights Piracy

A non-negligible **economic damage**

[2]Duck (Kurzgesagt), Shrimp (Jellycat London), Masterball (Nintendo)

Side-Channel Analysis

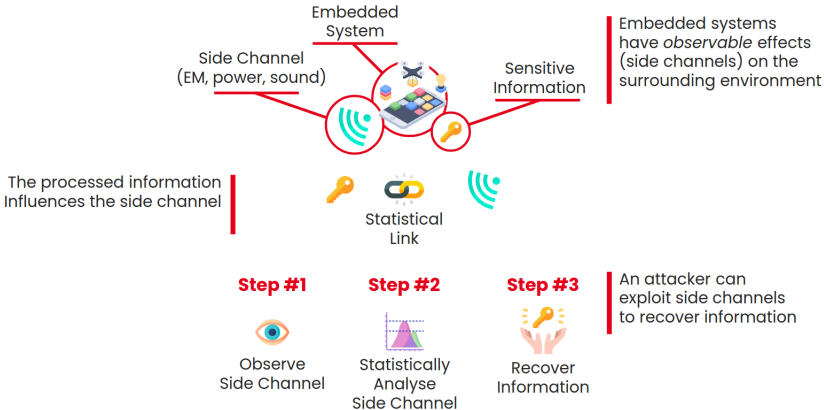
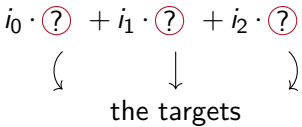


Figure: Side-Channel Analysis.

Side-channel Driven Weight Extraction



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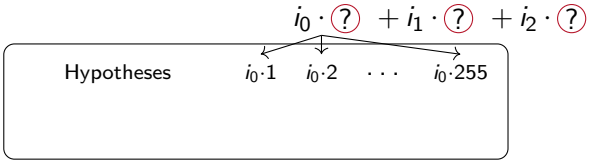

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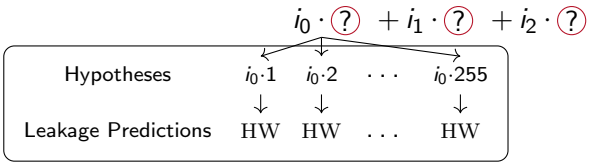

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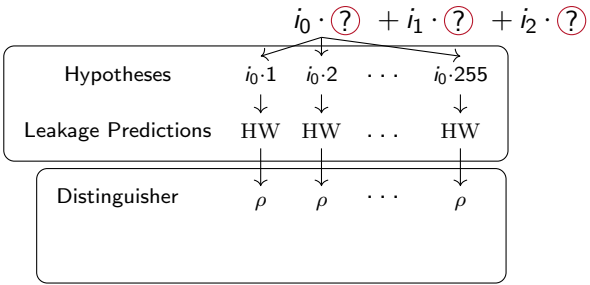

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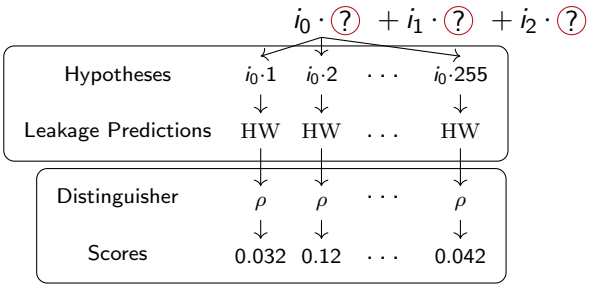

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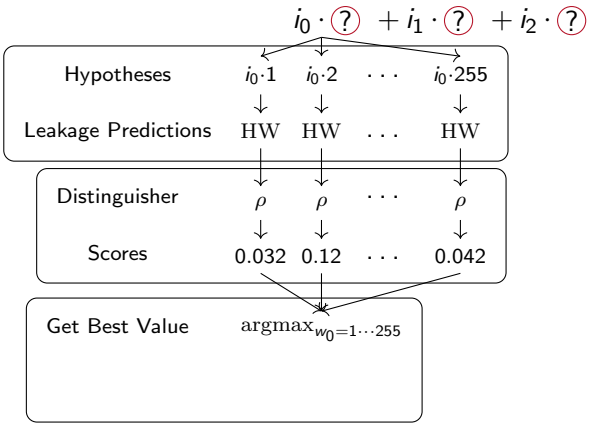

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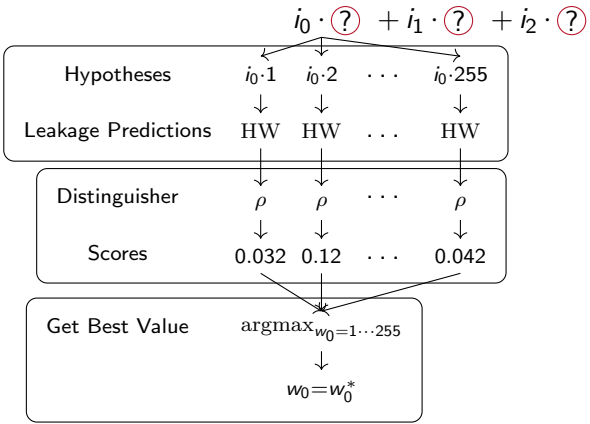
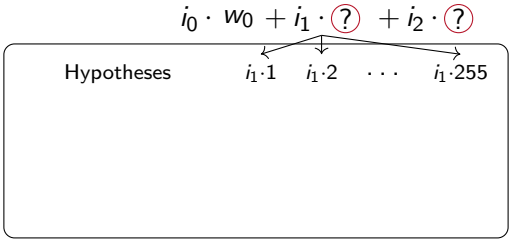


Side-channel Driven Weight Extraction

$$i_0 \cdot w_0 + i_1 \cdot \textcircled{?} + i_2 \cdot \textcircled{?}$$

Side-channel Driven Weight Extraction



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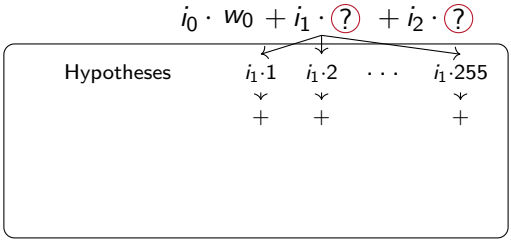

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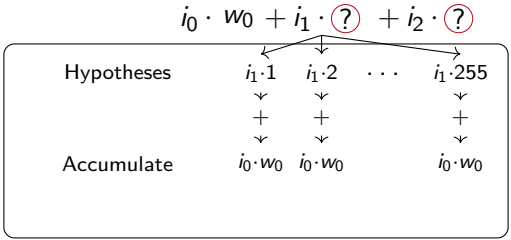

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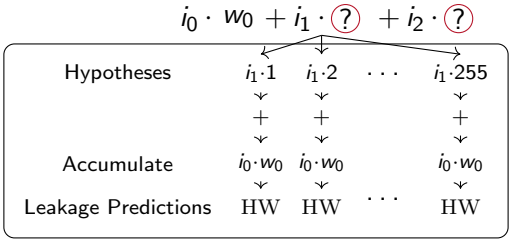

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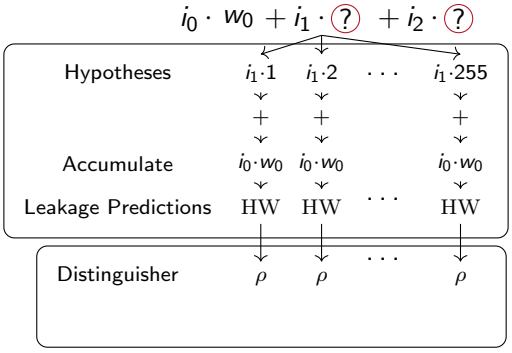

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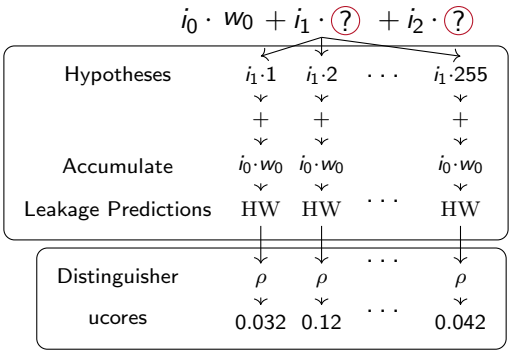

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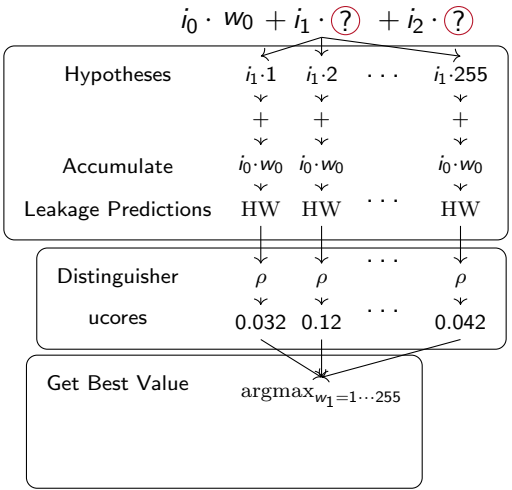

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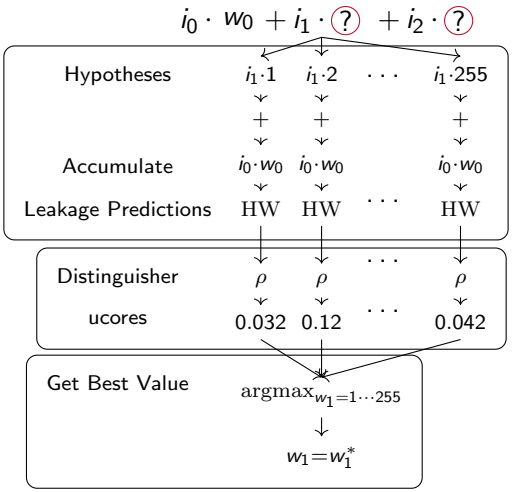

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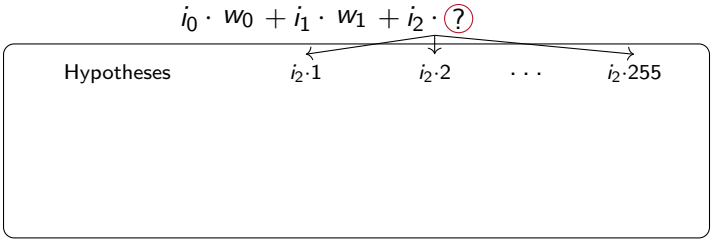

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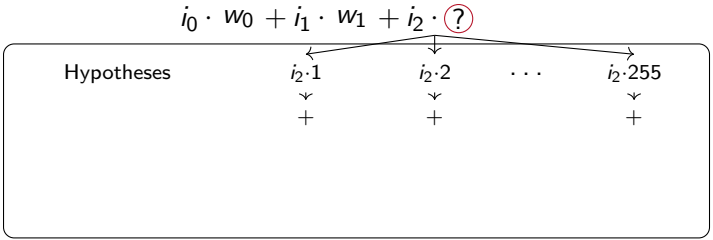

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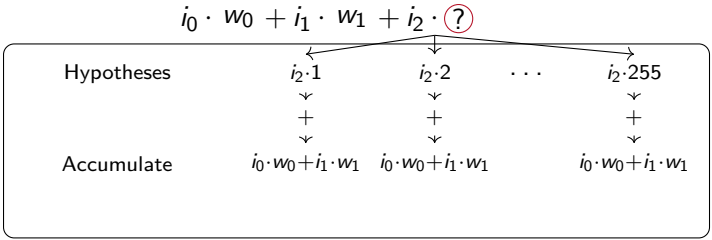

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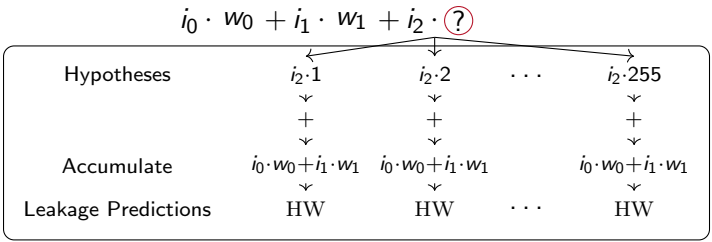

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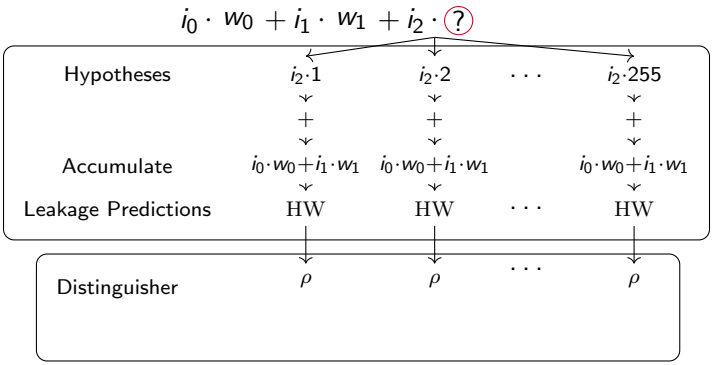

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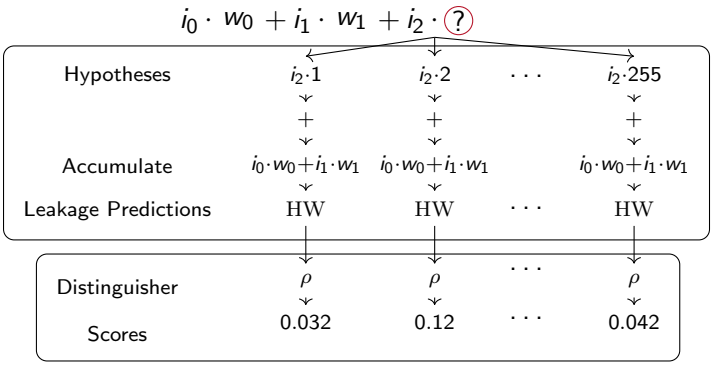

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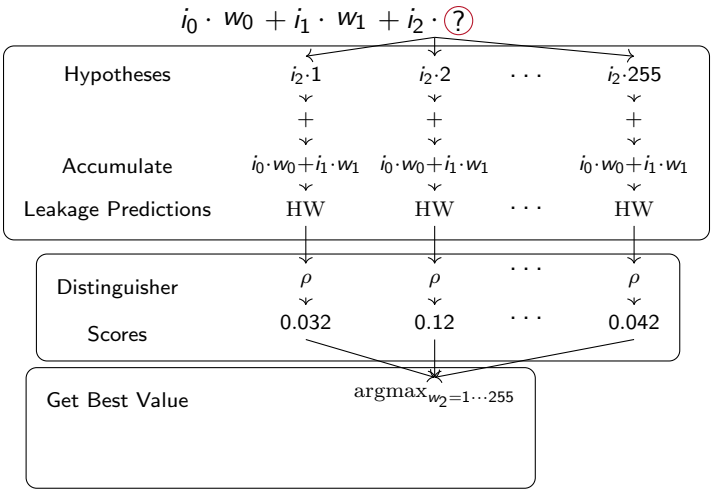

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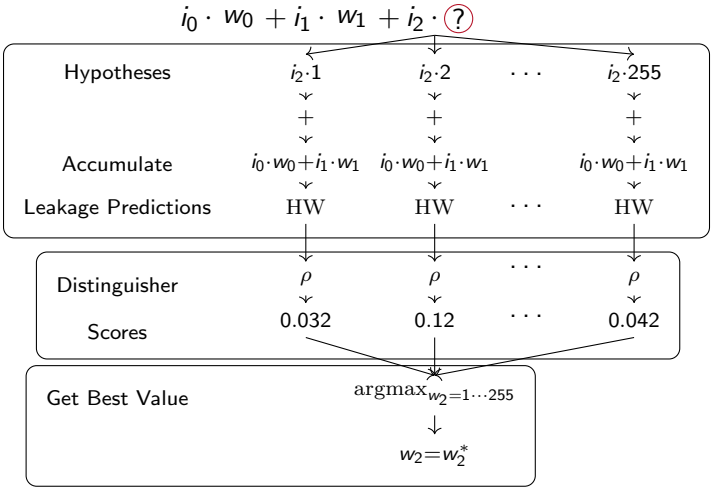


Side-channel Driven Weight Extraction

$$i_0 \cdot w_0 + i_1 \cdot w_1 + i_2 \cdot w_2$$

Countermeasures

Masking

Replace the weight-dependent signal with N random ones

Shuffling

Randomly shuffle operations to bury weight-dependent signal in signal noise

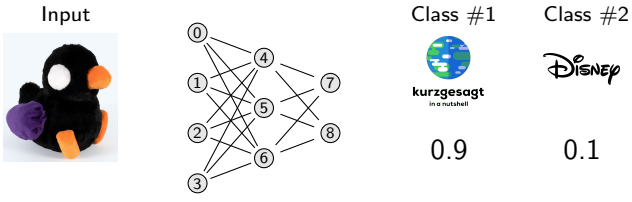
DNN-Tailored Countermeasures

- Current defences come from cryptanalysis
- But DNNs $\neq$ cryptosystems!
- DNNs exhibit particular characteristics (e.g., error resilience)

Approximate Computing

A Definition [Leo+25]

Intentional insertion of errors to **trade** *tunable* **accuracy** *loss* **for** *valuable* **resource gains**.



Original Network

Approximate Computing

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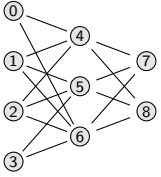
Input



Class #1

kurzgesagt
in a nutshell

0.7

Class #2

Disney

0.3

Pruned Network

Approximate Computing

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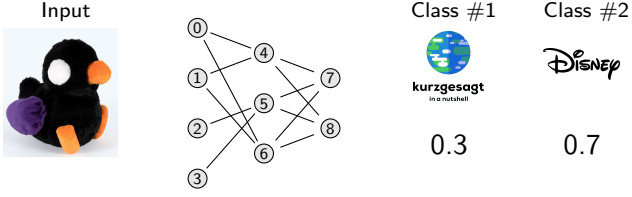

Approximate Computing and Side-Channel Behaviour

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Approximate-Computing (AxC)-based Countermeasures

- Approximation changes the application behaviour

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- Approximation changes the application's *side-channel signature*

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- Approximation changes the application behaviour
- Approximation changes the application's *side-channel signature*
- What role does AxC play in side-channel resilience? [Jap+25; Zha+26]

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  - Core question of the ANR "ATTILA" project

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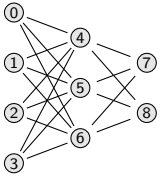
Approximate-Computing (AxC)-based Countermeasures

- Approximation changes the application behaviour
- Approximation changes the application's *side-channel signature*
- What role does AxC play in side-channel resilience? [Jap+25; Zha+26]
  - Core question of the ANR "ATTILA" project
- Recently considered as a side-channel countermeasure [Din+25]

Pixel Importance

Input



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0.9

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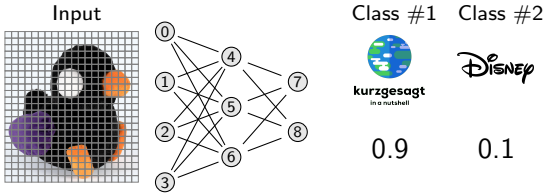
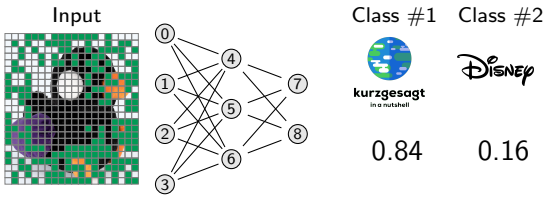
0.1

Pixel Importance



- What happens if we *prune* (skip) pixels?

Pixel Importance



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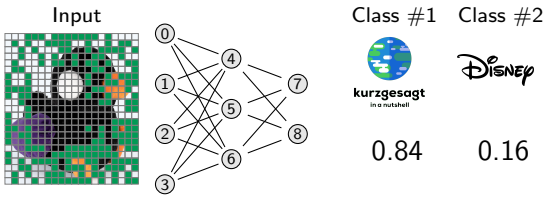
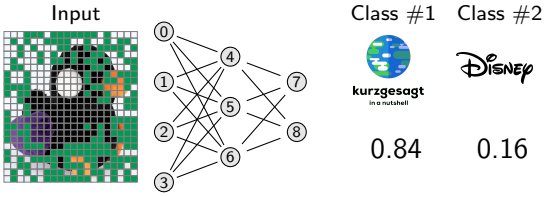


- What happens if we *prune* (skip) pixels?
- Non-important pixel: negligible accuracy reduction
  - Non-important weight

Pixel Importance



- What happens if we *prune* (skip) pixels?
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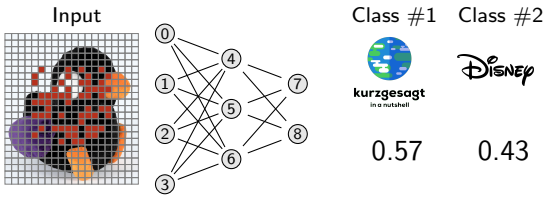
  - Non-important Multiply-and-Accumulate (NIMAC)

Pixel Importance



- What happens if we *prune* (skip) pixels?
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  - Non-important weight
  - Non-important Multiply-and-Accumulate (NIMAC)
- Important pixel: important accuracy reduction

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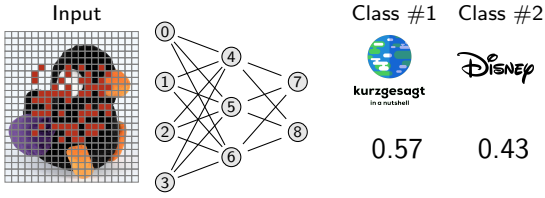

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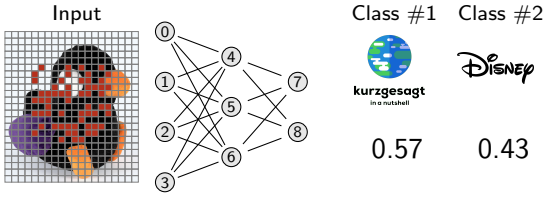

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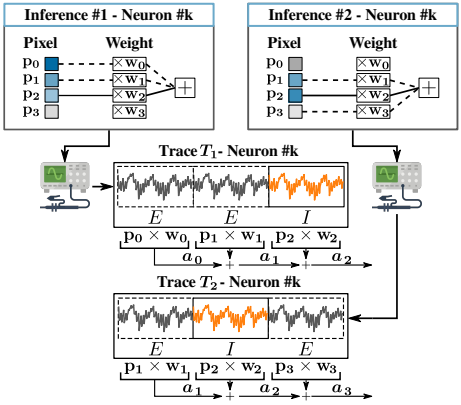
- Important pixel: important accuracy reduction
  - Important weight
  - Important MAC (IMAC)

MACPruning

The Idea

At each inference, randomly skip (*prune*) non-important pixels.



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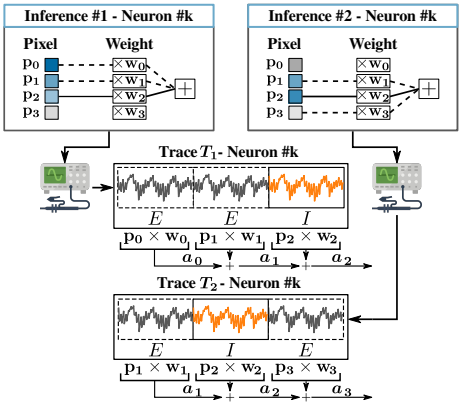
Effects



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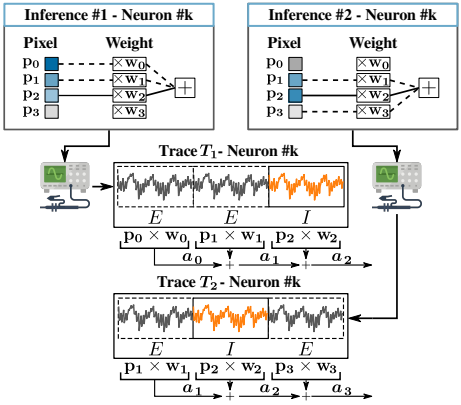
At each inference, randomly skip (*prune*) non-important pixels.

Effects

- **Incorrect leakage predictions**,



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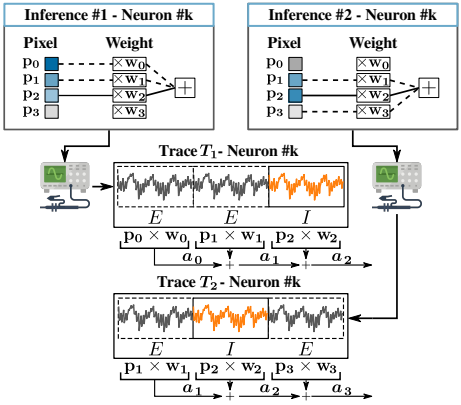
Effects

- **Incorrect leakage predictions**,
- **Desynchronised traces**.



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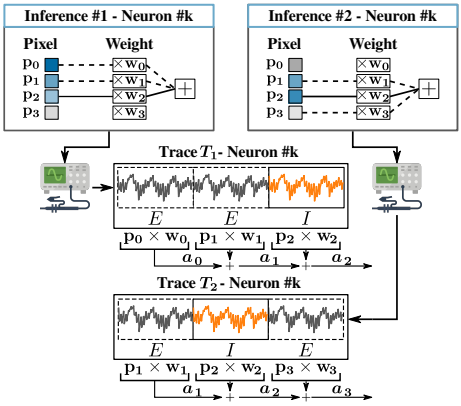
Security Implications

Successful weight recovery requires exponential number of traces.



MACPruning Implementation

Input : *inputs*: $(w \times h)$-array of pixels
weights: $(w \times h)$-array of weights
IaPAM: $(w \times h)$-array of bits
randWords: $(w \times h)$-array of bits
Output: *acc*: accumulator

```
1  acc ← 0;
2  for i from 0 to length(inputs) do
   |
   |
   |
   |
   |
   |
   |
   |
   |
10 end
```

The Idea

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The Implementation Logic

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At each inference, randomly skip (*prune*) non-important pixels.

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- IaPAM: pixel $\mapsto$ importance,

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Control-flow Dependency and Side-channel Information

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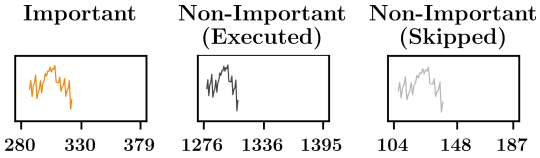

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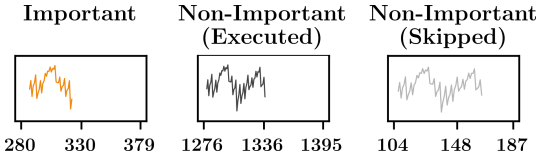

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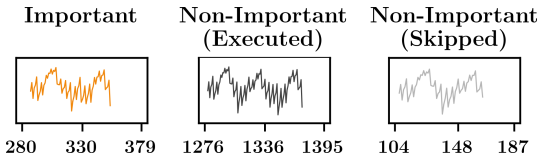

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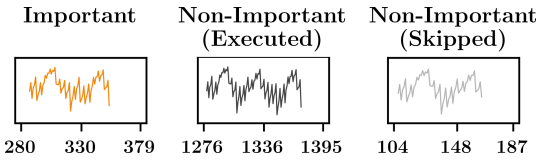

Side-Channel Information

Control-flow dependency hints each pixel' importance

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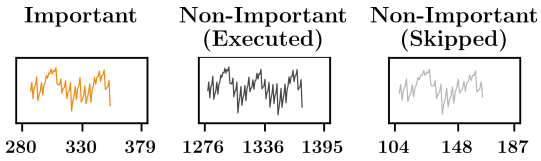

Side-Channel Information

Control-flow dependency hints each pixel' importance

Question

What are the security implications?

Control-flow Dependency and Security Implications

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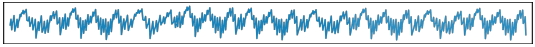

Control-flow Dependency and Security Implications

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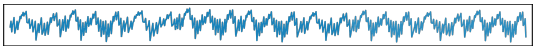

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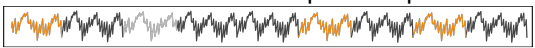
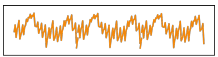


i_0 i_1 i_2 i_3 i_4 i_5 i_6 i_7 i_8



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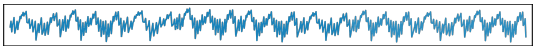

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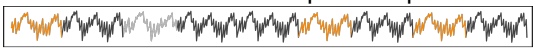

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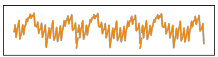

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↓

Circumvent trace desynchronisation

Control-flow Dependency and Security Implications

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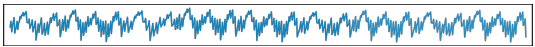

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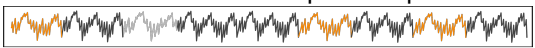

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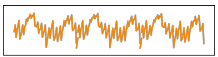

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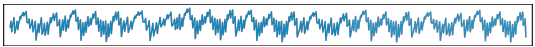

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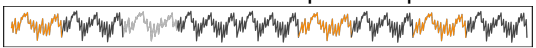

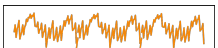

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Compute correct leakage predictions

Control-flow Dependency and Security Implications

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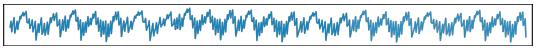

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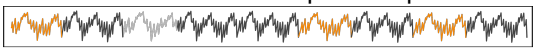

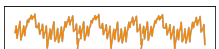

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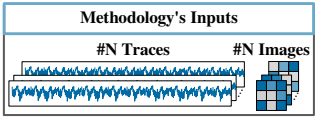
Compute correct leakage predictions

Research Question

Can we circumvent the MACPruning countermeasure?

Table of Contents

A Preprocessing Methodology to Circumvent MACPruning



Goal

Recover the Important Weights.

Methodology

Figure: Preprocessing Methodology.

A Preprocessing Methodology to Circumvent MACPruning

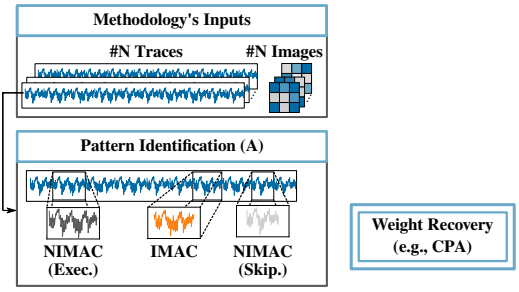


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Figure: Preprocessing Methodology.

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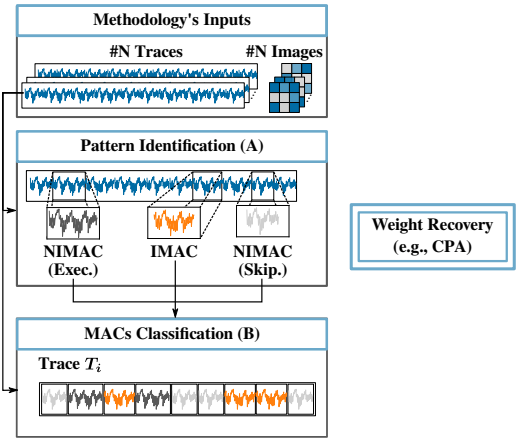

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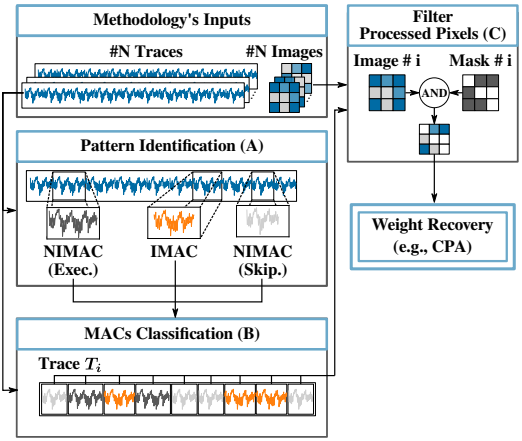

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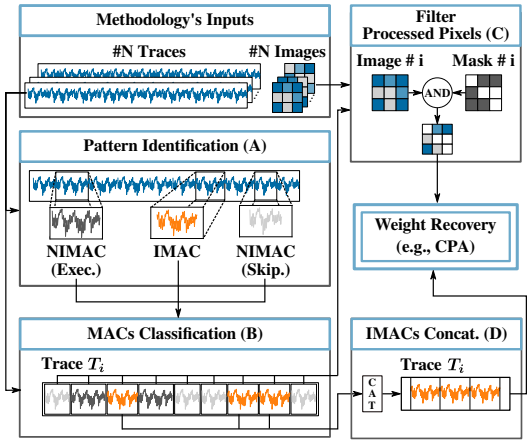

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Methodology

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B. Identify MAC;/Inputs importance in traces;
C. Remove skipped pixels from images;
D. Preserve only the important MACs.

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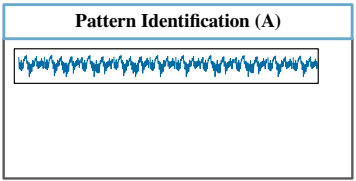
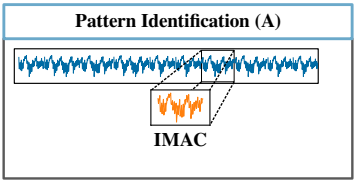


Pattern Identification

- Given one (or more) trace(s)...
- Identify a pattern for:

Step A – Pattern Identification



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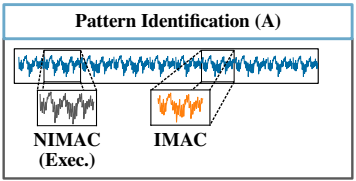

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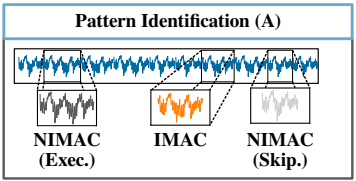

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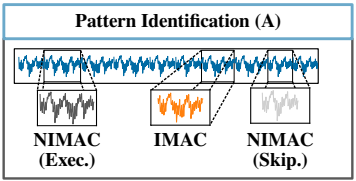

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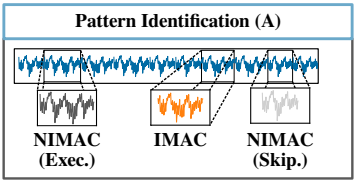

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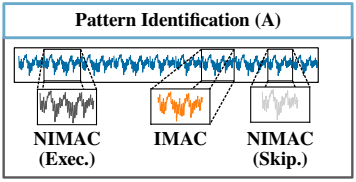

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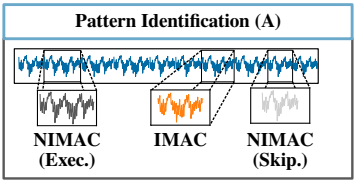
Multiple patterns

- **Caveat:** one MAC may have multiple patterns

Step A – Pattern Identification



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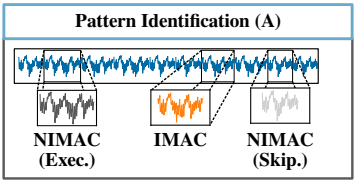
Multiple patterns

- **Caveat:** one MAC may have multiple patterns
  - Multiple instructions issue
  - Out-of-order architectures

Step A – Pattern Identification



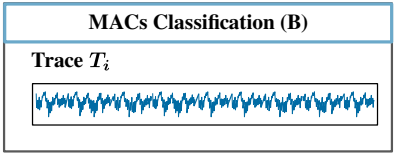
Pattern Identification

- Given one (or more) trace(s)...
- Identify a pattern for:
  - Important MACs (IMAC);
  - Non-important *executed* MACs (NIMAC);
  - Non-important *skipped* MACs
- Manual or automated search

Multiple patterns

- **Caveat:** one MAC may have multiple patterns
  - Multiple instructions issue
  - Out-of-order architectures
- We assume to have 1 pattern per MAC (scalar architecture)

Step B – MACs Classification



Sliding-Window Pattern Matching

1. Define an acceptance threshold t;
2. Sliding each pattern p on each trace sample s;
3. For each pattern p, compute a distance score $d_p = d(p, T_i)$;
4. Assign to sample s pattern p if and only if:
   - $\forall p' \neq p : d_p > d_{p'}$
   - If $d(p, T_i) > t$, assign pattern to sample s;
5. Repeat from 2;

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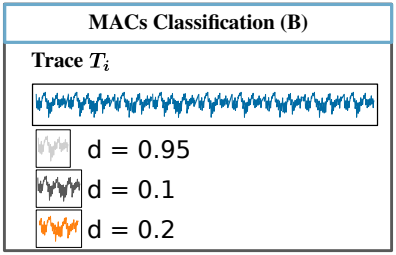

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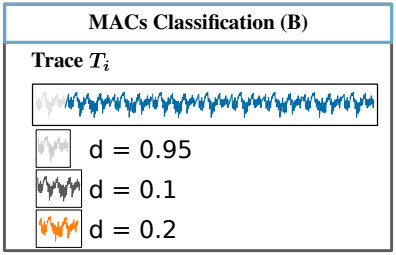

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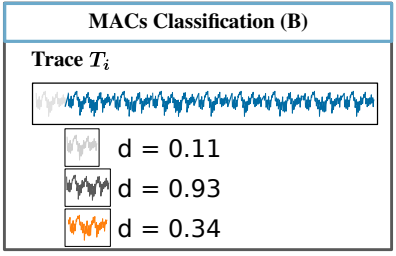

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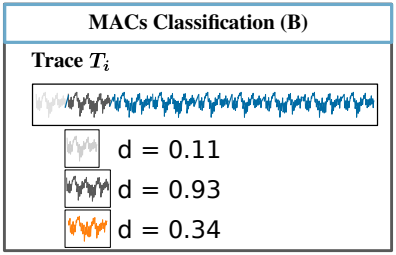

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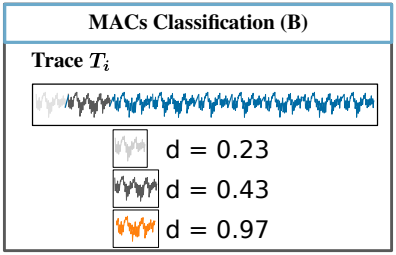

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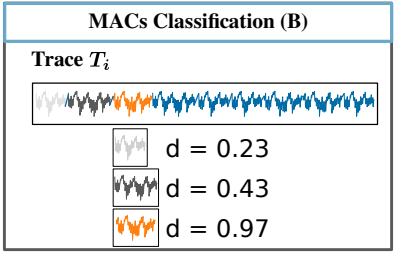

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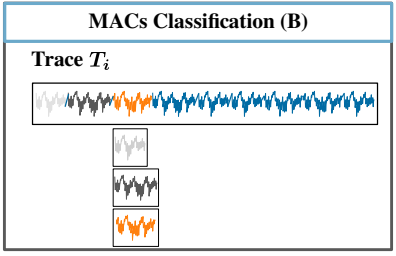

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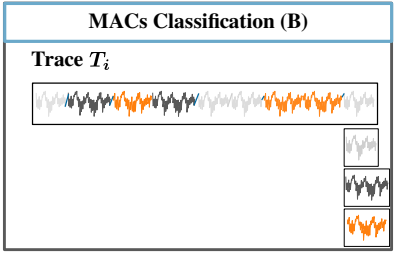

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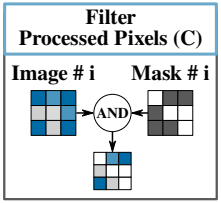
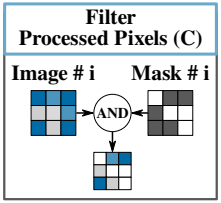
Step C – Filter Processed Pixels



Filter Processed Pixels

- Remove skipped pixels/MACs
- Allow for correct hypotheses computation

Step C – Filter Processed Pixels



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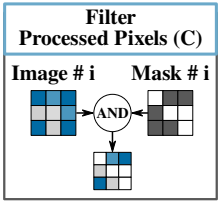

i_2	i_5	i_8
i_1	i_4	i_7
i_0	i_3	i_6

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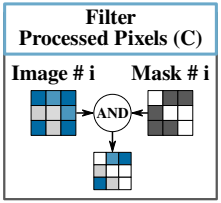

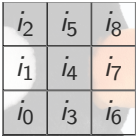

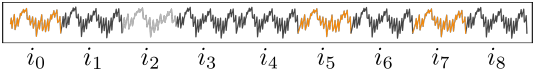

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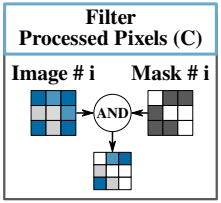

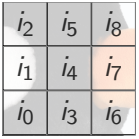

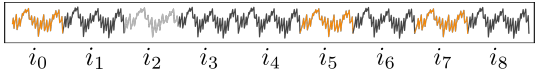

Filter Processed Pixels

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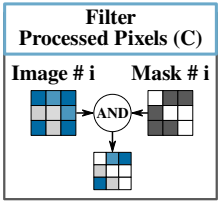
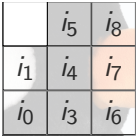
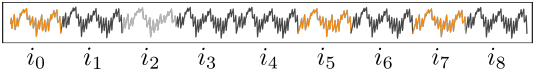
To recover w_5:

Step C – Filter Processed Pixels







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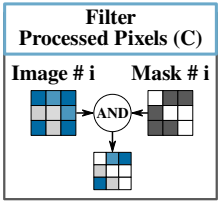

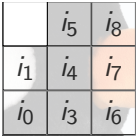

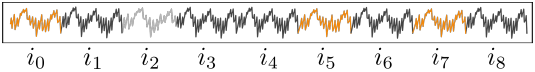

Filter Processed Pixels

- Remove skipped pixels/MACs
- Allow for correct hypotheses computation

To recover w_5:

$$w_0 \cdot i_0 + i_1 \cdot w_1 + i_2 \cdot w_2 + i_3 \cdot w_3 + i_4 \cdot w_4 + i_5 \cdot w_5$$

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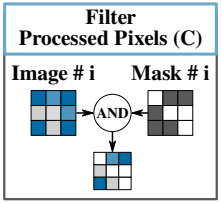

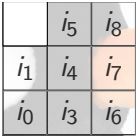

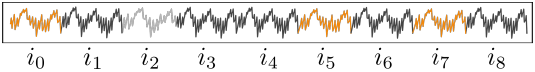

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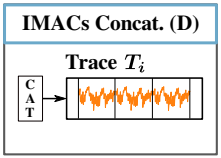
Step D – IMACs Concatenation



IMACs Concatenation

- Our goal: recover the Important MACs

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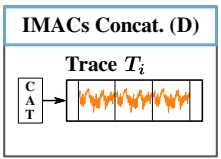

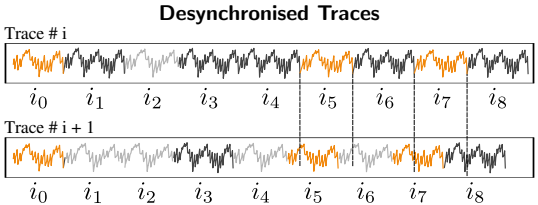

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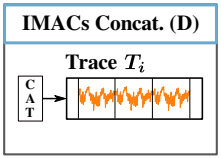
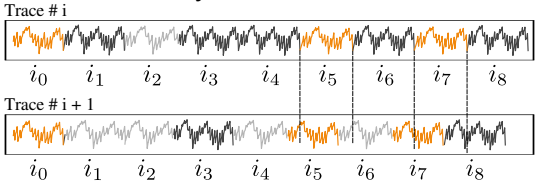


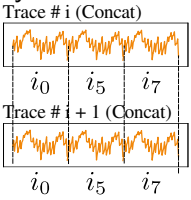
Desynchronised Traces



IMACs Concatenation

- Our goal: recover the Important MACs
- Preserve only the related patterns

Synchronised Traces



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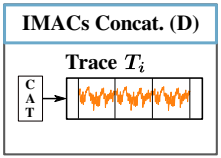

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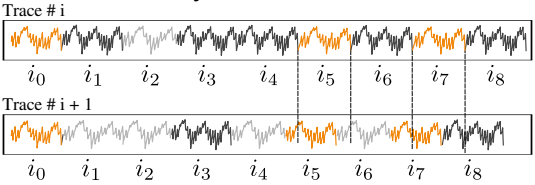


IMACs Concatenation

- Our goal: recover the Important MACs
- Preserve only the related patterns
- By-product: traces vertically aligned

Synchronised Traces

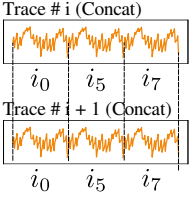


Table of Contents

Experimental Setup

Deep Neural Network model

- Multi-Layer Preceptron
- 5 neurons in the first layer
- 32 pixels per neuron

Side-channel Setup

- ARM Cortex-M4 (Clk = 7.37MHz)
- Chipwhisperer Lite (Sampling rate = x4 Clk)

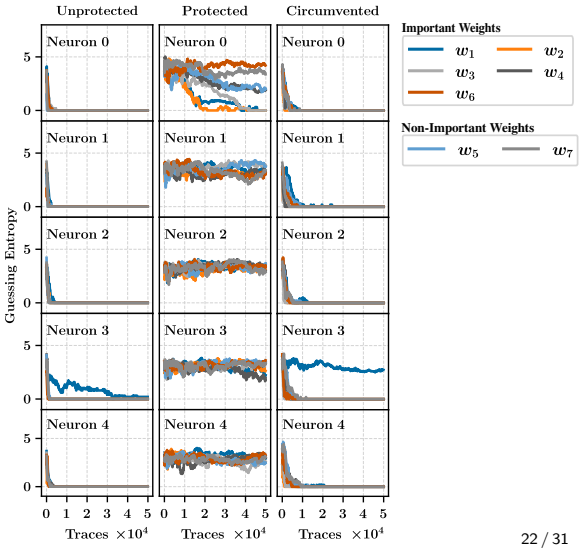
Experimental Procedure and Results

Experimental Procedure

1. Randomly and fix Important Pixels/MACs
2. Generate 5 sets of 50k random images
3. Recover 5 sets of 50k side-channel traces
4. Attack each set with Correlation Power Analysis
   - For each set, sort w_i's values in descending order
5. Compute the *Guessing Entropy (GE)* of w_i:
   - Average position of the true weight value
   - If $GE(w_i) = 0 \rightarrow$ true weight scores the best

Results

- Recovered all the important weights



Summary Pt. 1

MACPruning:
Exponentially increases number of traces for successful weight extraction

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Summary Pt. 1

MACPruning:
Exponentially increases number of traces for successful weight extraction

MACPruning Implementation:
Control-flow dependency (CFD) on pixel's importance

Our Work:
Preprocessing methodology to exploit the CFD-induced side-channel leakage

Results:
Extracted important weights with comparable number of traces of an unprotected MLP

Summary Pt. 1

Question:
What if we remove the control-flow dependency?

MACPruning: Fundamentally Broken?

Algorithm 4: Pseudo-code of a generic inference procedure enhanced with a control-flow-free MACPRUNING implementation.

Input : $inputs$: $(w \times h)$-array of pixels
$weights$: $(w \times h)$-array of weights
$IaPAM$: $(w \times h)$-array of bits
$randWord$: $(w \times h)$-array of bits
Output: acc: accumulator

```
1 acc ← 0;
2 for i from 0 to length(inputs) do
3 |   cond ← toSkip(IaPAM[i], randWord, i);
4 |   fn ← cond*addr(exec())+(1−cond)*addr(skip());
5 |   acc ← fn(inputs[i], weights[i], acc);
6 end
7 return acc;
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A Branchless MACPruning

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A Branchless MACPruning

- `toSkip`: check whether to process pixel i

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A Branchless MACPruning

- `toSkip`: check whether to process pixel *i*
  - Store result in *cond*

MACPruning: Fundamentally Broken?

Algorithm 4: Pseudo-code of a generic inference procedure enhanced with a control-flow-free MACPruning implementation.

Input : $inputs$: $(w \times h)$-array of pixels
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Output: acc: accumulator

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1 acc ← 0;
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7 return acc;
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A Branchless MACPruning

- `toSkip`: check whether to process pixel *i*
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Another Side-Channel Leakage

- `exec()` and `skip` different by design

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- We identify important weights,
- Confidence bound on the number of traces.

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Secure Approximate Computing might trade off accuracy for *security*

Thank You!

Questions?

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Microarchitectural Leakage

Unsuccessful Attacks?

- Not possible to recover the weight w_7
- Why?
- Solution: consider extended traces

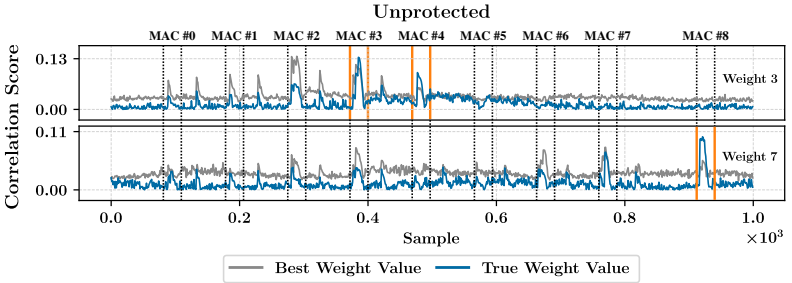

Figure: Microarchitectural Leakage.

Recovery of Non-Important Weights

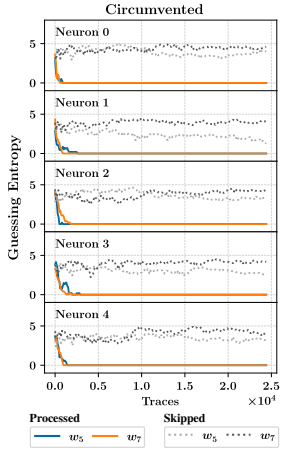

Figure: GE Filtered Traces.

Information carrying

- Partition traces in two sets:
  - *Processed*: non-important weight w_i processed
  - *Skipped*: non-important weight w_i skipped
- Compute GE on both sets
- Filtered traces carry information on non-important weights