



# Compilation for the Composition of Software Protections for Embedded Systems

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## ► To cite this version:

Thierno Barry, Damien Couroussé, Bruno Robisson. Compilation for the Composition of Software Protections for Embedded Systems. 5ème édition de la rencontre Crypto'Puce, May 2015, Île de Porquerolles, France. cea-01273410

**HAL Id: cea-01273410**

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Submitted on 13 Feb 2016

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FROM RESEARCH TO INDUSTRY

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# Compilation for the composition of software protections for embedded systems

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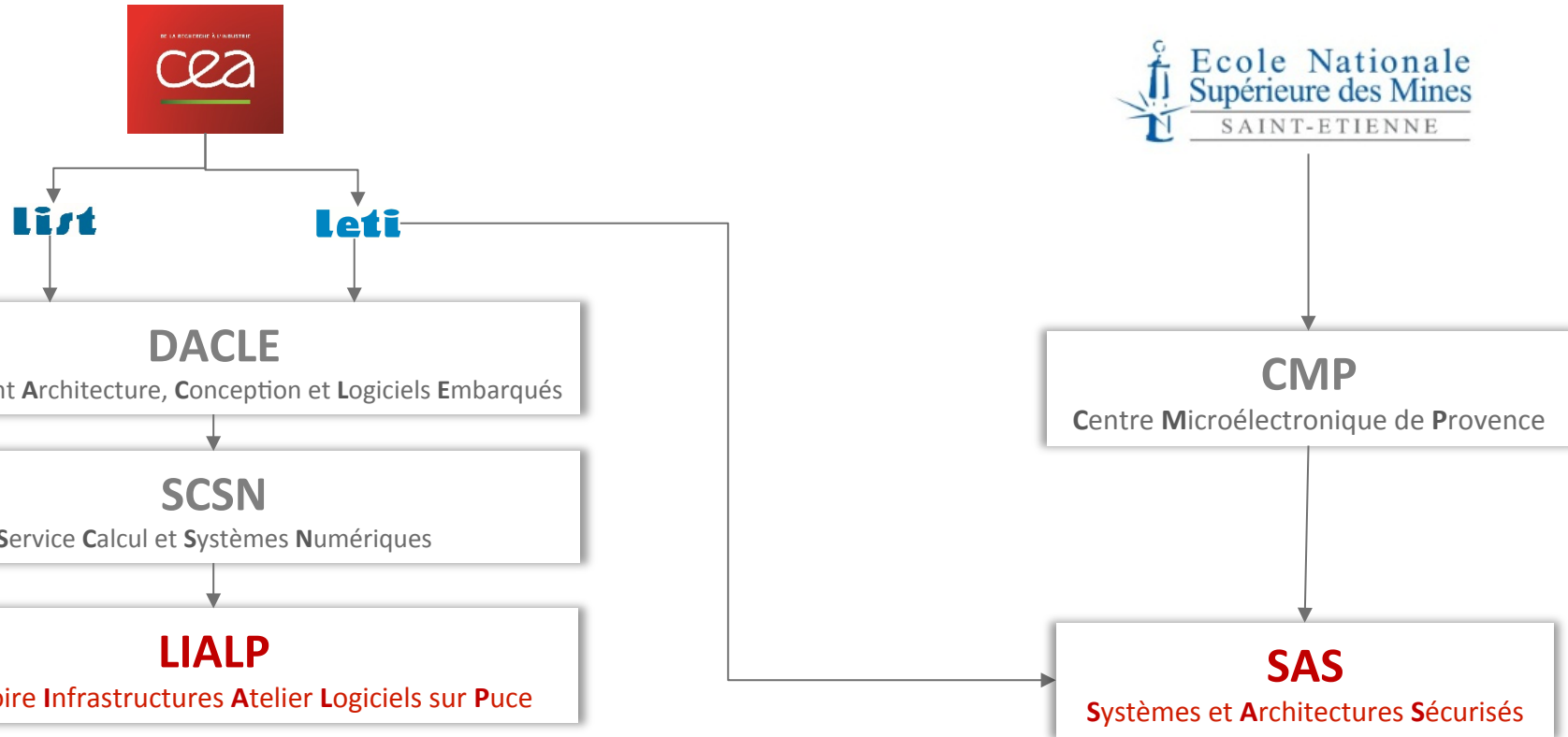
Crypto'Puce 2015

Porquerolles Tuesday, May 5, 2015

[www.cea.fr](http://www.cea.fr)

leti & list





- Automatic control (centralized and distributed )
- Middleware and communication
- Compilation and code generation
- Methods and tools: design flow for HW/SW integration

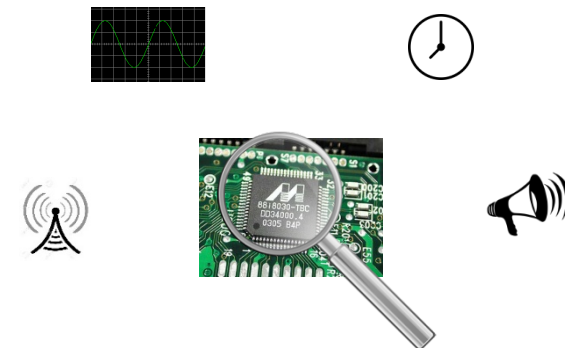
- Hardware security

- Nowadays, embedded systems have increasingly become critical part of our daily life
- One of the major threats against these systems are **physical attacks**

There are two main categories

## 1 Side channel attacks

Observing physical quantities of the device during operation



## 2 Fault attacks

Injecting a fault in order to disrupt the normal functioning of the device



- Proposing a **tool** for composing several software protections against physical attacks
- Through a compilation toolchain
- Our work involves two disciplines:
  - 1 Physical security
  - 2 Compilation



also called: **Compilation for security**

- Existing countermeasures against physical attacks
  - Concluding remarks
- Our approach
- A safari inside a compiler
  - why compilation + security is not obvious ?
- Why operating inside a compiler?
- First results
- Outlook

## Side Channel Attacks

- Work because there is a correlation between the operations being processed and some observable physical quantities

- The objective of countermeasures is:



- Two concepts:

### 1 Masking

Concealing each intermediate value  $v$  by a random value  $m$  such as:  $v_m = v \text{ op } m$



### 2 Hiding



- Software

- Insertion of dummy instructions
- Instructions shuffling

- Hardware

- Randomize the power consumption
- Equalize the power consumption

$$\begin{aligned} v_m &= v \oplus m && \rightarrow \text{Boolean} \\ v_m &= v + m && \rightarrow \text{Modular addition} \\ v_m &= v \times m && \rightarrow \text{Modular multiplication} \end{aligned}$$

## Fault Attacks

### ■ Based on fault models where an attacker can:

- Skip an instruction
- Replace an instruction with another one
- Corrupt data being transferred from/to memory

### ■ Proposed countermeasures are:

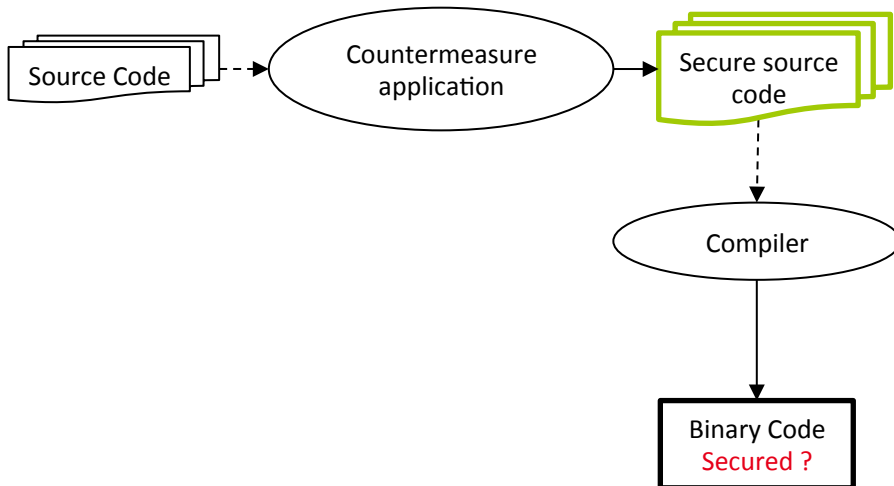
- Instructions redundancy
- Control flow hardening
- CRC / Parity Check / ...



## Concluding

- We notice two approaches for applying countermeasures

### 1 At the source code level



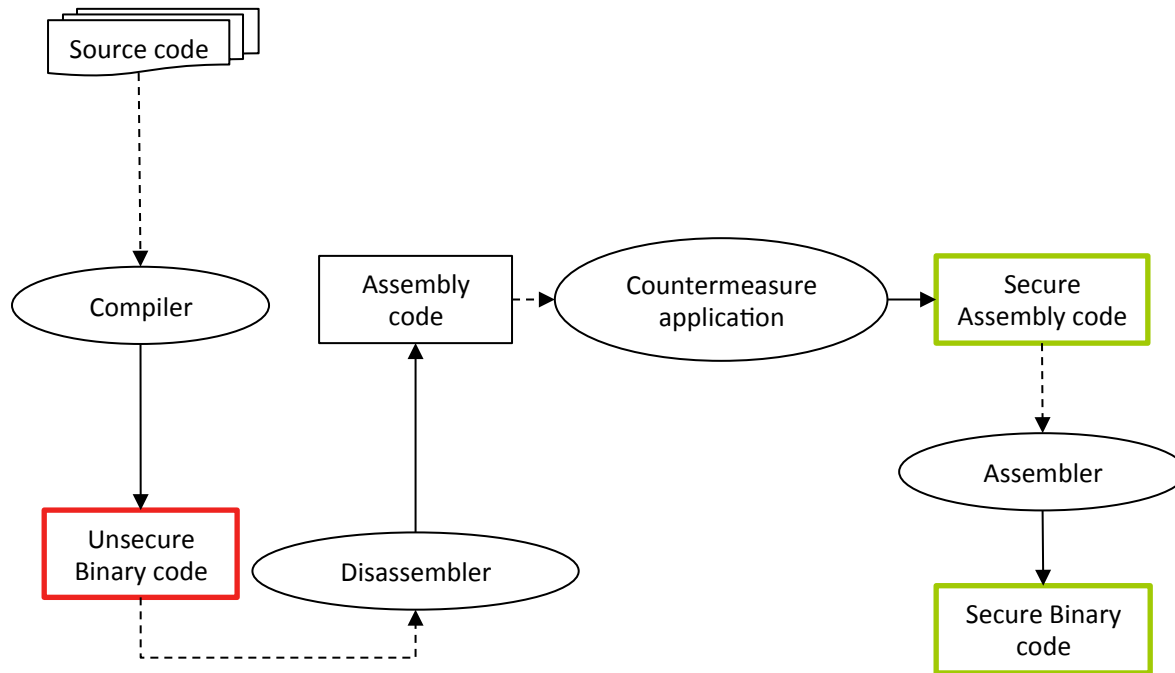
*source to source approach*

## Problems:

- None of security properties applied to the source code are guaranteed after the compilation
- Except if all the compiler code optimizers are disabled as suggested in [\[Eldib et al. 2014\]](#)
- Leads to very high execution overheads:  
➔ + 400% in [\[Lalande et al. 2014\]](#)

## Concluding

### 2 At Assembly level



*Assembly approach*

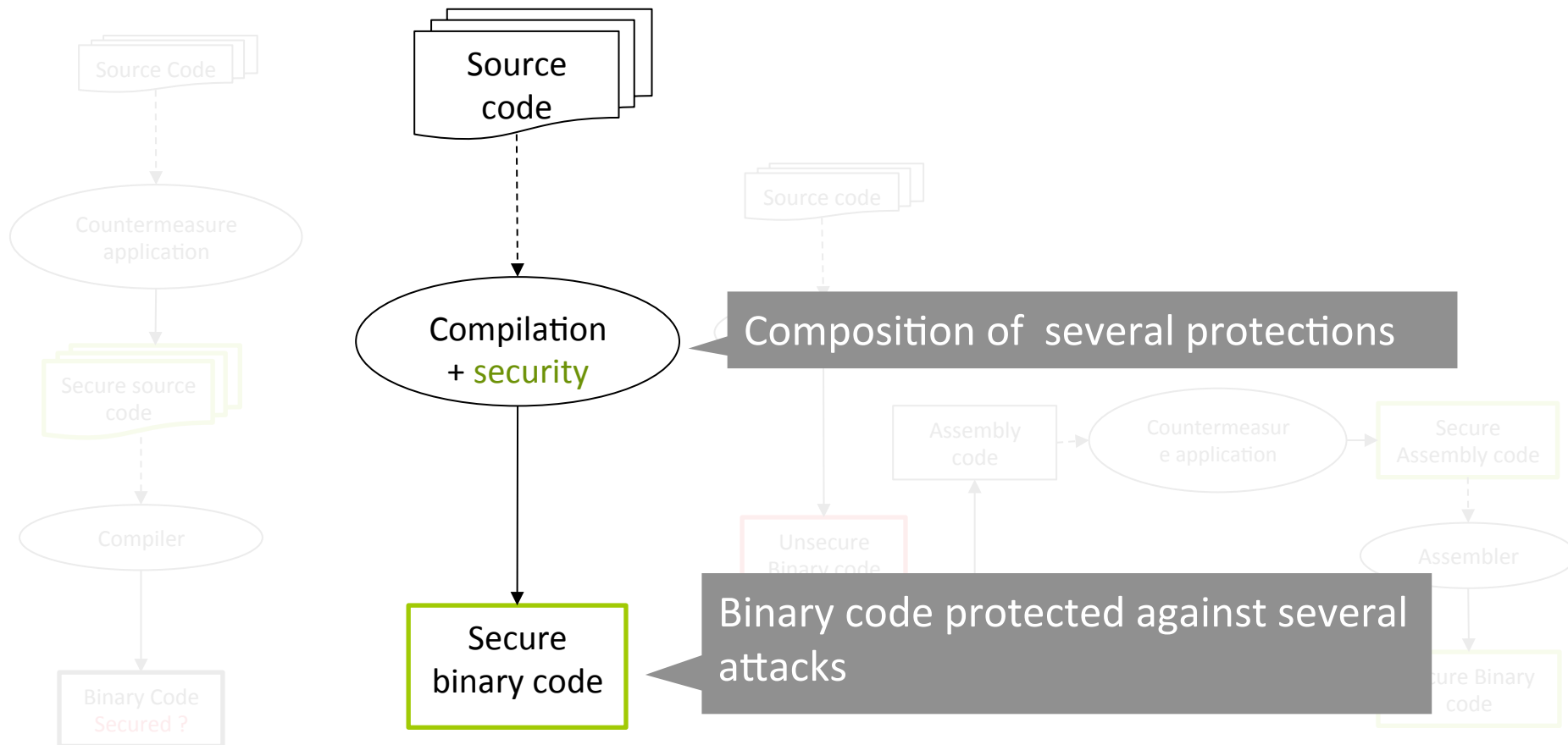
### Problems:

- Lack of visibility program context  
→ Overheads ++
- Often ad-hoc [Barengi et al., 2010]

## Concluding

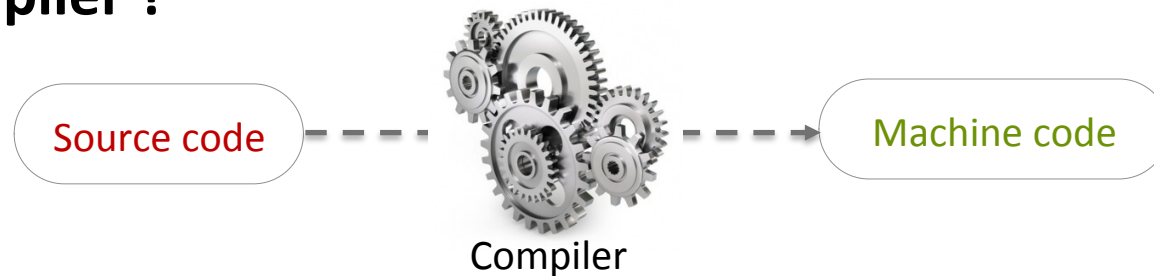
- A countermeasure is designed to protect against one single attack
- [Regazzoni et al. 2008] and [Luo et al. 2014] have shown that a code protected against Fault attacks may increase the power leakage  
→ and then become more vulnerable to power analysis attacks

How to take into account several threats inside a countermeasure ?

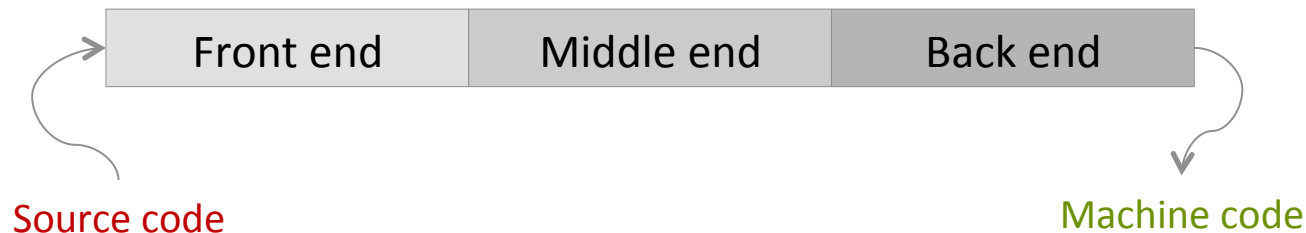


- Existing countermeasures against physical attacks
  - Concluding remarks
- Our approach
- A safari inside a compiler
  - why compilation + security is not obvious ?
- Why operating inside a compiler?
- First results
- Outlook

## What is a compiler ?



- The source code passes through several transformations and representation before the Machine code
- Each one is suitable for some kind of tasks of the compiler
- Modern compilers are structured in 3 phases:



## Front end

```
If (x > 0){
    return a+b;
}
```

Source code

```
...
%cmp = icmp sgt i32 %x, 0
br i1 %cmp, label %if.then, ...

%if.then:
    %add = add nsw i32 %a, %b
    store i32 %add, i32* %retval
    br label %return
...
```

Lexical  
Analysis

Syntax  
Analysis

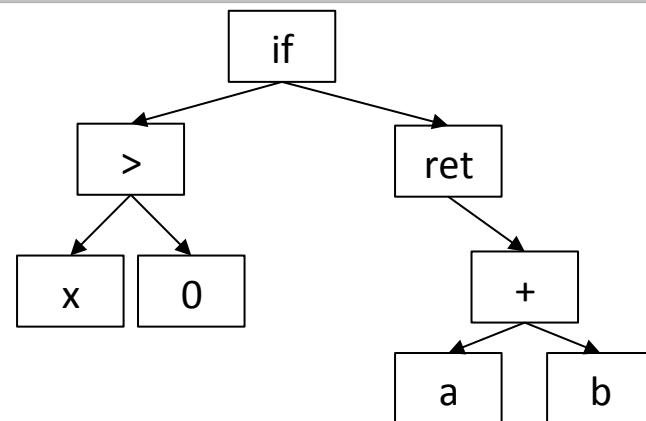
Type  
Checking

IR  
generation

Reads the **source code** and splits it into a list of tokens e.g.:

if	(	x	>	0	)	{
Return	a	+	b	;	}	

Take the list of tokens, build the AST → check the validity of the syntax



## Middle end

- Takes as input the Intermediate representation
- The IR is supposed to be language and target independent



- A countermeasure applied at the *middle end* remain valid for all languages and targets supported by the compiler



## Middle end

- The majority of code optimizer are applied at *middle end*
- Among them we have:
  - Global Value Numbering (GVN)
  - Dead Code Elimination (DCE)
  - Dead Store Elimination (DSE)

Remove all redundant instructions

Remove all unreachable instructions

Remove memory writings that are never read

```
int x = 0;
int y = f(x);
for(int i=1; i<= 100; i++)
    if(i > 0)
        x = x + 1;
    else
        x = x - 1;
y = f(x)
```

```
int x = 0;
int y = f(x);
for(int i=1; i<= 100; i++)
    x = x + 1;
y = f(x)
```

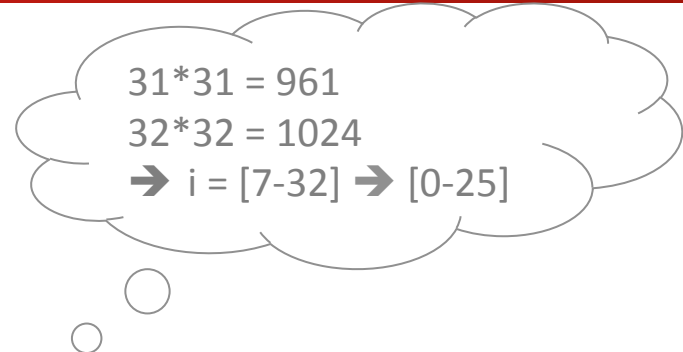
```
int x = 0;
int y = f(x);
x = 100;
y = f(x)
```

```
int y = f(100);
```

```
int y = f(0);
int x = 100;
y = f(x)
```

## Middle end

- Loop Invariant Code Motion (LICM)
- LOOP-UNROLLING / LOOP UNSWITCH



```
bool flag;
for(int i=7; i*i< 1000; i++){
    flag = verdict(1);
    if(flag == true)
        foo();
    else
        bar();
}
```



```
bool flag;
for(int i=0; i<25; i++){
    flag = verdict(1);
    if(flag == true)
        foo();
    else
        bar();
}
```



```
bool flag = verdict(1);
if(flag == true)
    for(int i=0; i<25; i++)
        foo();
else
    for(int i=0; i<25; i++)
        bar();
```



```
bool flag = verdict(1);
for(int i=0; i<25; i++){
    if(flag == true)
        foo();
    else
        bar();
}
```

## Back end

Takes the IR as input

- Instructions selections

Convert the IR to a representation close to the target architecture

- Register allocation

Find the best way to assign physical registers to variables in order to reduce register pressure and avoid memory spills

- Instruction scheduling

Rearrange instructions to obtain the best execution order in order to avoid *stalls* inside the pipeline

- Machine code emission

Emit executable code that is target-specific

	COMPILATION	SECURITY
GOAL	<ul style="list-style-type: none"> <li>■ Generation of executable code for a target architecture</li> <li>■ Making the execution as fast as possible</li> </ul>	<ul style="list-style-type: none"> <li>■ Safety</li> <li>■ Resistance against attacks</li> </ul>
How?	<ul style="list-style-type: none"> <li>■ Removing any instruction redundancy</li> <li>■ Dead code/store elimination</li> <li>■ Smart scheduling</li> <li>■ Simplifying and combining operation</li> </ul>	<ul style="list-style-type: none"> <li>■ Adding instruction redundancy</li> <li>■ Insertion of dummy instructions</li> <li>■ Random scheduling (<i>shuffling</i>)</li> <li>■ Masking intermediate values</li> </ul>

- 1 We have a complete view on the program being compiled
  - Possibility to reduce the cost of the security
- 2 We have control over code optimizers
  - We can decide where and when to apply security
  - We can ensure that the security won't be removed by the compiler
  - We can take advantage of code optimization
- 3 We can scale the security level relative to optimization level

## Instruction duplication (ID) inside the compiler

**1** With a very optimal overhead thanks to our hacked register allocator

### WHY?

With an **Assembly** approach, when comes to duplicate an instruction like: `add R0, R0, R1`

Just doing

```
add R0, R0, R1
add R0, R0, R1
```

is invalid because R0 is both source and destination

An extra available register is needed to save R0:

```
mov R2, R0
add R0, R2, R1
```

```
mov R2, R0
mov R2, R0
add R0, R2, R1
add R0, R2, R1
```

### How to find an extra available register?

**1** you are designing an ad-hoc countermeasure and you know how many registers are available [Barenghi et al., 2010]

**2** you parse your assembly code (not easy)

**3** Save an restore

```
push R2
mov R2, R0
add R0, R2, R1
pop R2
```

```
push R2
mov R2, R0
mov R2, R0
add R0, R2, R1
add R0, R2, R1
pop R2
```

## Instruction duplication (ID) inside the compiler

**1** With a very optimal overhead thanks to our hacked register allocator (RA)

We modified our RA in such a way that the destination register is always different to source registers:

`opcode Rdst, Rsrc1, Rsrc2` (Rdst != Rsrc1) and (Rdst != Rsrc2)

### THAT'S WHY

Instead of generating: `add R0, R0, R1`

We automatically generate: `add R0, R1, R2`

and duplicating such an instruction is straightforward

`add R0, R1, R2`  
`add R0, R1, R2` X 2

with a reduced overhead compared to:

X 4

```
mov R2, R0
mov R2, R0
add R0, R2, R1
add R0, R2, R1
```

and X 6

```
push R2
mov R2, R0
mov R2, R0
add R0, R2, R1
add R0, R2, R1
pop R2
```

## Instruction duplication (ID) inside the compiler

- 1 With a very optimal overhead thanks to our hacked register allocator (RA)
- 2 Our duplication process is done before the instruction scheduling
  - The compiler will rearrange the instructions in order to find the best execution order
  - As a consequence:
    - ➔ duplicated instructions may not necessary be glued



➔ improve the execution speed



Our objective is not to produce new unknown countermeasure

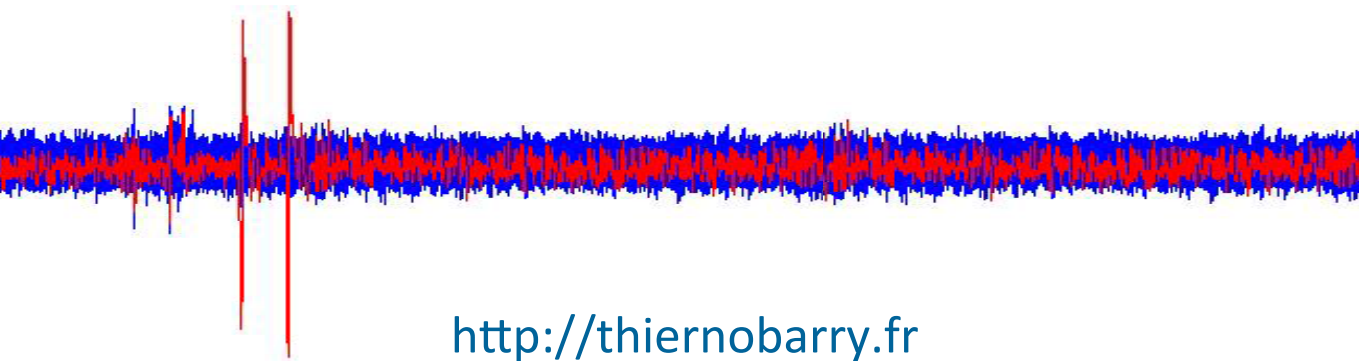
**BUT**

Finding a way to combine them in a single tool, without marginalizing the execution performance

- The next step is to implement power analysis countermeasures in our compiler
- And then implementing a unified countermeasure model
- Proving the validity of the model



Thank you for your attention



<http://thiernobarry.fr>



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