# A compositional methodology to harden programs against multi-fault attacks

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# Outline

# Faults injection - Example on `verify_pin`

PIN verification program from FISSC collection [Dureuil et al., 2016]

```
bool compare(uchar* a1, uchar* a2, size_t size)
{
    bool ret = true;
    size_t i = 0;
    for(; i < size; i++) // Fault
        if(a1[i] != a2[i])
            ret = false;

    if(i != size) // Countermeasure
        killcard();

    return ret;
}

bool verify_pin(uchar* user_pin) {
    if(try_counter > 0)
        if(compare(user_pin, card_pin, PIN_SIZE)) {
            // Authentication
            try_counter = 3;
            return true;
        } else {
            try_counter--;
            return false;
        }
    return false;
}
```

- Example of software fault model: *Test inversion*

  → inverse the branch taken during conditional branching

- **Software countermeasures (program transformations) can be placed to protect against faults**

# Faults injection - Example on `verify_pin`

PIN verification program from FISSC collection [Dureuil et al., 2016]

```
bool compare(uchar* a1, uchar* a2, size_t size)
{
    bool ret = true;
    size_t i = 0;
    for(; i < size; i++) // Fault 1
        if(a1[i] != a2[i])
            ret = false;

    if(i != size) // Fault 2 => countermeasure attack
        killcard();

    return ret;
}

bool verify_pin(uchar* user_pin) {
    if(try_counter > 0)
        if(compare(user_pin, card_pin, PIN_SIZE)) {
            // Authentication
            try_counter = 3;
            return true;
        } else {
            try_counter--;
            return false;
        }
    return false;
}
```

- Example of software fault model: *Test inversion*

  → inverse the branch taken during conditional branching

- **Software countermeasures (program transformations) can be placed to protect against faults**

  **multi-fault → countermeasures themselves can be attacked**

# Lazart results on VerifyPIN collection

**Lazart** [Potet et al., 2014] is an **LLVM**-level multi-fault robustness evaluation tool based on **Dynamic-Symbolic Execution** (KLEE).

**Fault models**

- Test/Branch inversion
- Data mutation (`load`) (symbolic)

| `verify_pin` version (from FISSC [Dureuil et al., 2016]) | countermeasures | 0-faults | 1-fault | 2-faults | 3-faults | 4-faults |
|---|---|---|---|---|---|---|
| vp_0 | ∅ | 0 | 3 | 0 | 0 | 1 |
| vp_1 | HB | 0 | 2 | 0 | 0 | 1 |
| vp_2 | HB+FTL | 0 | 2 | 1 | 0 | 1 |
| vp_3 | HB+FTL+INL | 0 | 2 | 1 | 0 | 1 |
| vp_4 | FTL+INL+DPTC+PTCBK+LC | 0 | 2 | 0 | 1 | 1 |
| vp_5 | HB+FTL+DPTC+DC | 0 | 0 | 4 | 4 | 1 |
| vp_6 | HB+FTL+INL+DPTC+DT | 0 | 0 | 3 | 0 | 1 |
| vp_7 | HB+FTL+INL+DPTC+DT+SC | 0 | 0 | 2 | 0 | 1 |

Legend:

- HB: hardened booleans
- FTL: fixed time loops
- INL: inlined function
- PTC: try counter decremented first
- PTCBK: try counter backup
- DC: double call
- LC: loop counter verification
- SC: step counter
- DT: double test
- CFI: control flow integrity [Lalande et al., 2014]

# Multiple faults and countermeasures

- State of the art attacks combine several faults to achieve their goal [Kim and Quisquater, 2007], [Natella et al., 2016], [Wookey/SSTIC20, 2020]

- Try-and-error approaches are unsuitable for multi-fault
  $\rightarrow$ countermeasures themselves can be attacked
  $\rightarrow$ testing all countermeasures placements is unrealistic

- Several tools use *systematic approach*, which could lead to unnecessary protections [Lalande et al., 2014, de Ferrière, 2019]

**Probl.**

How to help to place countermeasures and give guarantees on the protected program in multi-fault context ?

# Placement of software countermeasures

**Goal**: help to place countermeasures against multi-fault attacks wrt a set of fault models *M*

- Target **robustness** in (*at least*) *N* faults
- Using a catalog of countermeasures schemes with *Injection Point* (IP) granularity

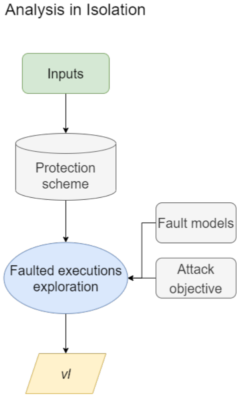
**Approach: compositional** analysis using:

1. **Isolation analysis** of protection schemes
   → Notion of *adequacy* and *vulnerability level*

2. **Placement algorithms**: select the protection to apply to each IP in the program
   → Using a representative set of attacks on the program wrt to *M*

# Outline

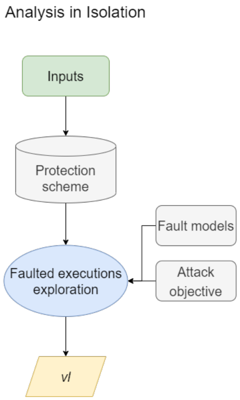
# Principle of analysis in isolation




**Analysis in isolation:** reusable analysis of multi-fault behavior of protection scheme

- *Single fault:* verify that the protection scheme correctly blocks successful attacks for the fault model $m \in M$ (**adequacy**), with $m$ the fault model of the unprotected IP

# Principle of analysis in isolation




**Analysis in isolation:** reusable analysis of multi-fault behavior of protection scheme

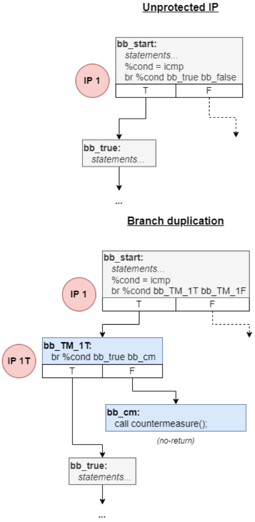
- *Single fault:* verify that the protection scheme correctly blocks successful attacks for the fault model $m \in M$ (**adequacy**), with $m$ the fault model of the unprotected IP
- *Multi fault:* research of the **vulnerability level** ($vl$) of the protection scheme:

  $\rightarrow$ e.g. *How many faults are required to induce an abnormal behavior (not detected) for the protected IP ?*

  $\rightarrow$ Unprotected IP has $vl = 1$

  $\rightarrow$ Can be computed with Lazart

# Analysis in isolation of Branch duplication scheme



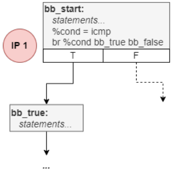

Branch Duplication: duplication of a conditional branch

Isolation analysis with *Branch Inversion* fault model

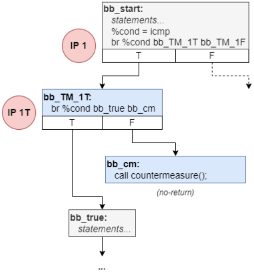
Search of the minimal number of faults required to invalidate the nominal behavior

# Analysis in isolation of Branch duplication scheme

Unprotected IP




Branch duplication




Branch Duplication: duplication of a conditional branch

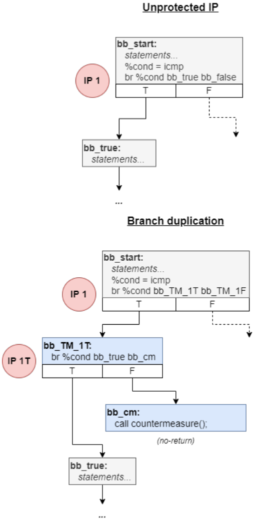
Isolation analysis with *Branch Inversion* fault model

Search of the minimal number of faults required to invalidate the nominal behavior

Need to define :

- Nominal countermeasure behavior:
  - Input(s) of the scheme
  - Output(s) of the scheme
  - Entry point(s)
  - Output point(s)
  - Nominal behavior
- Attack surface

# Analysis in isolation of Branch duplication scheme

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Isolation analysis with *Branch Inversion* fault model

Search of the minimal number of faults required to invalidate the nominal behavior

Need to define :

- Nominal countermeasure behavior:
  - Input(s) of the scheme → **the `%cond` temporary**
  - Output(s) of the scheme → **the destination branch**
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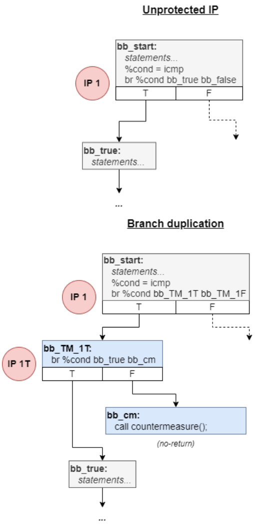
# Analysis in isolation of Branch duplication scheme

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Isolation analysis with *Branch Inversion* fault model

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Need to define :

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  - Input(s) of the scheme → **the** `%cond` **temporary**
  - Output(s) of the scheme → **the destination branch**
  - Entry point(s) → **the** `br` **instruction (**`bb_start`**)**
  - Output point(s) → **the destination block (**`bb_true`**)**
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- Attack surface

# Analysis in isolation of Branch duplication scheme

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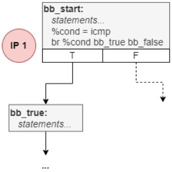
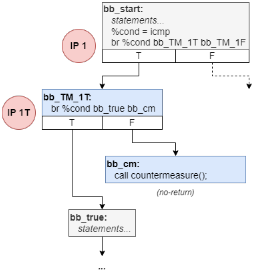



Branch duplication

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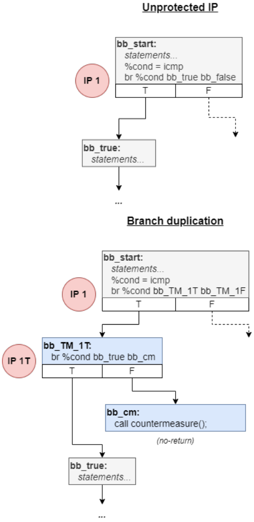
  - Output point(s) $\rightarrow$ **the destination block (**`bb_true`**)**
  - Nominal behavior $\rightarrow$ **reach** `bb_true` **if and only if %cond is true**
    $\Rightarrow$ corresponds to the post-condition to be verified
- Attack surface

# Analysis in isolation of Branch duplication scheme

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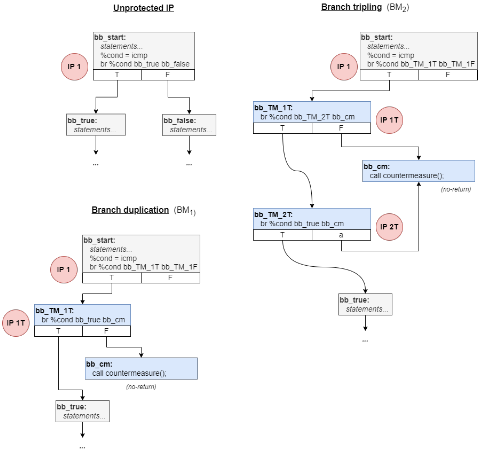
  - Nominal behavior → **reach** `bb_true` **if and only if %cond is true**
    ⇒ corresponds to the post-condition to be verified
- Attack surface → *IP* 1 **and** *IP* 1*T* **with BI fault model**

# Analysis in isolation of BM schemes



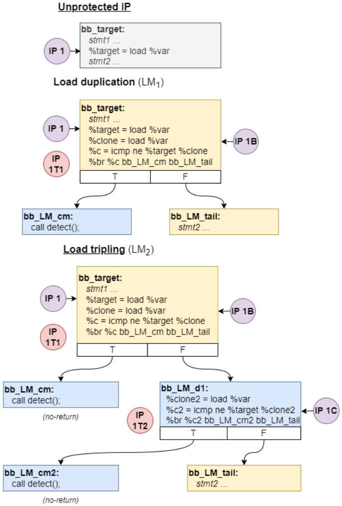

**Branch Multiplication** ($BM_n$): n-plication of a conditional branch

Isolation analysis with *Branch Inversion* fault model

| Countermeasure | 0-faults | 1-fault | 2-faults | 3-faults | *vl* |
|---|---|---|---|---|---|
| $BM_0$ | 0 | 1 | 0 | 0 | **1** |
| $BM_1$ | 0 | 0 | 1 | 0 | **2** |
| $BM_2$ | 0 | 0 | 0 | 1 | **3** |

Table: Vulnerability Level of $BM_n$

# Analysis in isolation of LM schemes




**Load Multiplication** ($LM_n$): n-plication of a `load` instruction (and checks)

Isolation analysis with *Data Load* and *Branch Inversion* fault models

- Input: the value stored in `%var` memory cell
- Output: the value loaded in `%target`
- Nominal behavior: `%target` stores `%var`'s value

| Countermeasure | 0-faults | 1-fault | 2-faults | 3-faults | *vl* |
|---|---|---|---|---|---|
| $LM_0$ | 0 | 1 | 0 | 0 | **1** |
| $LM_1$ | 0 | 0 | 1 | 0 | **2** |
| $LM_2$ | 0 | 0 | 0 | 1 | **3** |

Table: Vulnerability Level of $LM_n$

# Summary

*Analysis in isolation* computes properties about *protection scheme*:

- **Adequacy** determines if the protection scheme blocks the attack on the IP in single fault (equivalent to $vl > 1$)
- **Vulnerability level** corresponds to the minimal number of faults required by the attacker to produce an incorrect behavior

The countermeasures $BM_n$ and $TM_n$ have $vl = 1 + n$ (verified for $n \leq 4$ with Lazart)

$\rightarrow$ *Vulnerability level* will be used by placement algorithms to select which *adequate* protection scheme should be applied on which IP

# Outline

# Placement algorithms principles

**GOAL:** generate a P' program which is **robust** to *N* faults from a set of fault models *M*

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Basic structure of placement algorithms:

1. Obtain set of attack traces

   $\Rightarrow$ Computed with all fault models in $M$ and the user-defined attack objective
2. Compute **required vulnerability levels** ($vl_{ip}$) for each IP (initialized to 1)
3. Generate $P'$ with protection scheme matching the **required vulnerability levels**

   $\Rightarrow$ Using a catalog $\mathcal{C}$ of countermeasures (with computed $vl_{ip}$)

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Three approaches:

- *Systematic* placement: protect all IPs of a set with $vl > N$
- *Block* placement: protect at least one IP for each attacks with $vl > N$
- *Distributed* placement: protect IPs such as for each attack trace, the sum of $vl_{ip}$ is greater than $N$

# Systematic placement algorithms

Table: Principle of each placement algorithms

| Approach | Algorithm | Description |
|---|---|---|
| **Systematic** | **naive** | **All IPs in $P$ are protected with $vl > N$** |
| **Systematic** | `atk` | All IPs in attacks are protected with $vl > N$ |
| **Systematic** | `min` | All IPs in minimal attacks are protected with $vl > N$ |
| Block | `block` | At least one IP per minimal attacks is protected with $vl > N$ |
| Distributed | `opt` | Protection is distributed between the IPs in minimal attacks, to get rid of attacks in less than $N + 1$ faults. |

**Systematic placement approach**: protect with $vl > N$ an entire set of IPs

Naive placement algorithm (`naive`): protect **all** IPs in the program with $vl > N$

$\rightarrow$ *corresponds to standard systematic protection tools*

$\rightarrow$ does not require attacks paths

# Systematic placement algorithms

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**Systematic placement approach**: protect with $vl > N$ an entire set of IPs

Attacks placement algorithm (`atk`): protect **all** IPs in the set of attacks $A$ in the program with $vl > N$

$\rightarrow$ $A$ is a *representative* set of successful and non detected attacks for $P$ wrt $M$, meaning that each ordered sequence of faulted IP leading to a successful and non detected attacks is in $A$

# Systematic placement algorithms

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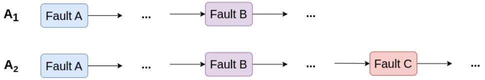
| Block | `block` | At least one IP per minimal attacks is protected with $vl > N$ |
| Distributed | `opt` | Protection is distributed between the IPs in minimal attacks, to get rid of attacks in less than $N + 1$ faults. |

**Systematic placement approach**: protect with $vl > N$ an entire set of IPs

Minimal attacks placement algorithm (`min`): protect **all** IPs in in the set of attacks $A$ in the program with $vl > N$

**Definition (Redundant and Minimal)**

An attack $a'$ is *redundant* wrt an attack $a$ if the word of faulted transition of $a$ is a **proper prefix** of the faulted transition word of $a'$
An attack is *minimal* if it isn't redundant to any other attack



# Block placement algorithm

Table: Principle of each placement algorithms

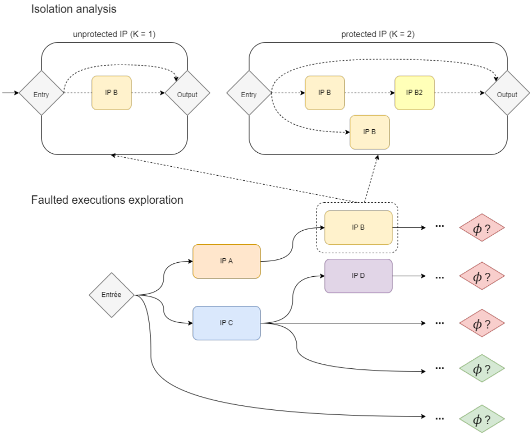
| Approach | Algorithm | Description |
|---|---|---|
| Systematic | `naive` | All IPs in $P$ are protected with $vl \geq n+1$. |
| Systematic | `atk` | All IPs in attacks are protected with $vl \geq n+1$. |
| Systematic | `min` | All IPs in minimal attacks are protected with $vl \geq n+1$. |
| **Block** | **block** | **At least one IP per minimal attacks is protected with** $vl \geq n+1$**.** |
| Distributed | `opt` | Protection is distributed between the IPs in minimal attacks, to get rid of attacks in less than $n+1$ faults. |

**Block placement approach**: protect with $vl > N$ **at least** one IP per successful attack traces

Loop through all minimal attacks and if no IP is already protected by block ($vl > N$), select an IP to be protected with $vl > N$. Heuristic based:

- $\rightarrow$ start with attack with lower faults count
- $\rightarrow$ start with attack with the most redundant attacks associated
- $\rightarrow$ select the IP with the most occurence in minimal attacks to be protected

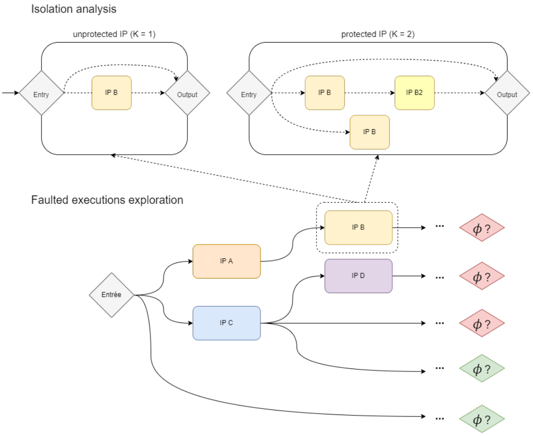
# Compositional analysis placement




- Isolation analysis for each considered protection scheme with all studied fault models
- Attacks traces gives guarantees on which IP violation can lead to an attack

  $\rightarrow$ *Here, IPA can be left unprotected if IPB is protected*

# Compositional analysis placement




- Isolation analysis for each considered protection scheme with all studied fault models
- Attacks traces gives guarantees on which IP violation can lead to an attack

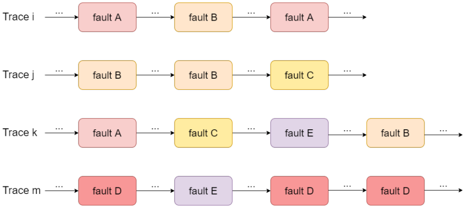
  $\rightarrow$ *Here, IPA can be left unprotected if IPB is protected*

$\Rightarrow$ **Protection can be distributed between the IPs**

# Optimal distributed placement

- Distribute protections of IPs inside minimal attacks traces to ensure at least N + 1 faults are required to obtain attacks
  $\longrightarrow$ usable if the catalog $\mathcal{C}$ does not contains CM for K > N

- An Integer Linear Programming (ILP) optimization problem
  $\longrightarrow$ attacks gives constraints on the protection to apply




$C_i = 2x_a + x_b > N$

$C_j = 2x_b + x_c > N$

$C_k = x_a + x_b + x_c + x_e > N$

$C_m = 3x_d + x_e > N$

Research of the **optimal** placement
$\Rightarrow$ minimize the protection weight $Z = x_a + x_b + \ldots + x_p$

- require to ensure that all states produced by the protected IPs are studied in trace exploration fault models
  $\longrightarrow$ *guarantees on partially protected IPs*

# Outline

# Experimentation - verify_pin

*verify_pin* [Dureuil et al., 2016] (**VP**): smart-card PIN verification process

- *fault model:* branch inversion
- *countermeasures:* branch multiplication (BM)

| Exp. | | | Algo. | $\sum$ of protections | | | | Robust |
|---|---|---|---|---|---|---|---|---|
| Program | Fault Model | IPs | | 1-fault | 2-faults | 3-faults | 4-faults | |
| `VP` | BI | 8 | `naive` | 8 | 16 | 24 | 32 | ✓ |
| | | | `atk` | **3** | 8 | 12 | 16 | ✓ |
| | | | `min` | **3** | 8 | 12 | 16 | ✓ |
| | | | `block` | **3** | **6** | **9** | **12** | ✓ |
| | | | `opt` | **3** | **6** | **9** | **12** | ✓ |

# Experimentations - `memcmps3`

*memcmps* v3 (**MCMPS**): secure version of `memcmp`.

- *fault model:* branch inversion + data load
- *countermeasures:* branch multiplication (BM) and load multiplication (LM)

| Exp. | | | Algo. | $\sum$ of protections | | | | Robust |
|---|---|---|---|---|---|---|---|---|
| Program | Fault Model | IPs | | 1-fault | 2-faults | 3-faults | 4-faults | |
| MCMPS | BI | 12 | `naive` | 12 | 24 | 36 | 48 | ✓ |
| | | | `atk` | **0** | **0** | **0** | 16 | ✓ |
| | | | `min` | **0** | **0** | **0** | 16 | ✓ |
| | | | `block` | **0** | **0** | **0** | 4 | ✓ |
| | | | `opt` | **0** | **0** | **0** | **1** | ✓ |
| MCMPS | DL | 15 | `naive` | 15 | 30 | 45 | 60 | ✓ |
| | | | `atk` | **1** | 6 | 15 | 32 | ✓ |
| | | | `min` | **1** | 6 | 15 | 32 | ✓ |
| | | | `block` | **1** | 4 | 6 | 8 | ✓ |
| | | | `opt` | **1** | **3** | **5** | **7** | ✓ |
| MCMPS | BI + DL | 27 | `naive` | 27 | 54 | 81 | 108 | ✓ |
| | | | `atk` | **1** | 8 | 24 | 56 | ✓ |
| | | | `min` | **1** | 8 | 24 | 56 | ✓ |
| | | | `block` | **1** | 6 | 9 | 12 | ✓ |
| | | | `opt` | **1** | **3** | **5** | **8** | ✓ |

# Experimentations - FU1

*firmware_updater* v1 (**FU**): updates a firmware from remote source

- *fault model:* branch inversion + data load
- *countermeasures:* branch multiplication (BM) and load multiplication (LM)

| Exp. | | | Algo. | $\sum$ of protections | | | | Robust |
|---|---|---|---|---|---|---|---|---|
| Program | Fault Model | IPs | | 1-fault | 2-faults | 3-faults | 4-faults | |
| `fu1` | BI | 42 | `naive` | 42 | 84 | 126 | 168 | ✓ |
| | | | `atk` | **0** | 28 | 42 | 88 | ✓ |
| | | | `min` | **0** | 28 | 42 | 72 | ✓ |
| | | | `block` | **0** | 14 | 21 | 28 | ✓ |
| | | | `opt` | **0** | **7** | **14** | **21** | ✓ |
| | DL | 2 | `naive` | 2 | 4 | 6 | 8 | ✓ |
| | | | `atk` | 1 | 4 | 6 | 8 | ✓ |
| | | | `min` | **1** | **2** | **3** | **4** | ✓ |
| | | | `block` | **1** | **2** | **3** | **4** | ✓ |
| | | | `opt` | **1** | **2** | **3** | **4** | ✓ |
| | BI+DL | 44 | `naive` | 44 | 88 | 132 | 176 | ✓ |
| | | | `atk` | **1** | 32 | 60 | 96 | ✓ |
| | | | `min` | **1** | 32 | 60 | 80 | ✓ |
| | | | `block` | **1** | 16 | 24 | 32 | ✓ |
| | | | `opt` | **1** | **9** | **17** | **25** | ✓ |

# Outline

# Summary

- Robustness of placement depends on the property of the catalog $\mathcal{C}$

- P' is guaranteed to be robust for N faults if the required protection coefficients (K) are available

  $\rightarrow$ if not, attack traces on P' are known

  $\rightarrow$ more robust than P even if trace set is incomplete

- Protection weight: *distributed* $\leq$ *block* $\leq$ *min* $\leq$ *atk* $\leq$ *naive*

  $\rightarrow$ Optimal placement is guaranteed with ILP

| Algorithm | Type | Guarantees $P'$ | | Complexity | Required analysis | | |
|---|---|---|---|---|---|---|---|
| | | Robust | Optimal | | AA | Red | HS |
| `naive` | syst. | ✓ | - | $O(t)$ | ✓ | - | - |
| `atk` | syst. | ✓ | - | $O(t)$ | ✓ | - | - |
| `min` | syst. | ✓ | - | $O(t)$ | ✓ | ✓ | - |
| `block` | block | ✓ | - | $O(t)$ | ✓ | ✓ | ✓ |
| `opt` | distributed | ✓ | ✓ | NP-Complete | ✓ | ✓ | - |

- Placement algorithm is fast compared to trace generation (DSE)

  $\rightarrow$ even with optimal algorithm and ILP (1-fault attacks)

# Future Work

**Conclusion:**

- Isolation analysis allows to reason about unprotected and protected IP out of the context of a particular program

  $\rightarrow$ vulnerability level quantifies guarantees of the CM wrt a set of fault models
- Placement algorithms gives strong guarantees, even if the trace set is incomplete

  $\rightarrow$ optimality of the placement guaranteed by ILP

# Future Work

**Conclusion:**

- Isolation analysis allows to reason about unprotected and protected IP out of the context of a particular program

  $\rightarrow$ vulnerability level quantifies guarantees of the CM wrt a set of fault models

- Placement algorithms gives strong guarantees, even if the trace set is incomplete

  $\rightarrow$ optimality of the placement guaranteed by ILP

**Future Work:**

- Study of countermeasures propagating states (SSCF, Swift...)

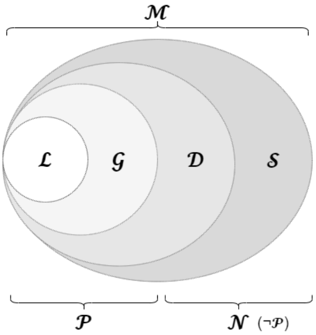
  $\rightarrow$ may require to consider two isolation analysis cases: sane CM's inputs and corrupted CM's inputs

- Study of more complex CFG fault models

  $\rightarrow$ requires to take into account the several entry and output points of the protection scheme

- Implementation of the approach on binary level

# Future Work - Model protectability




Fault models

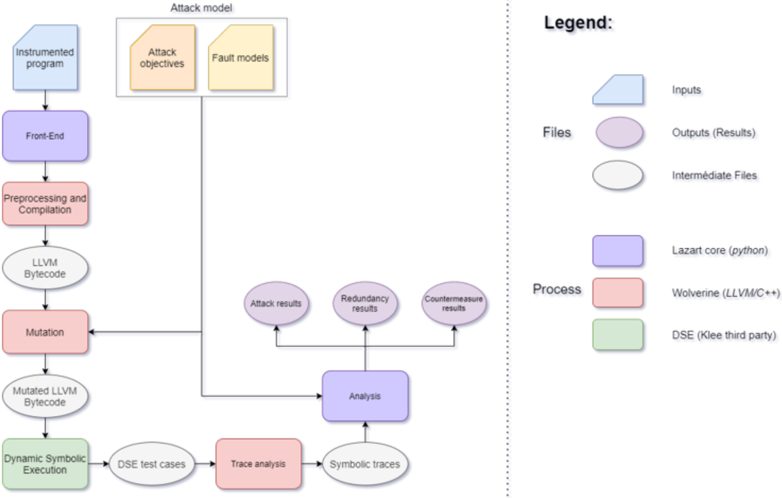
- $\mathcal{P}$ : Protectable
  - $\mathcal{L}$ : Locally Protectable
  - $\mathcal{G}$ : Globaly Protectable
- $\mathcal{N}$: Unprotectable
  - $\mathcal{D}$ : Diluable
  - $\mathcal{S}$ : Strictly unprotectable

- $\mathcal{L}$: it exists an IP granularity countermeasures with $vl > N$ for all $N > 1$ (Test Inversion, Data Load mutation)
- $\mathcal{G}$: $\exists cm$ such as $cm(P)$ is robust in $N$ faults
- $\mathcal{D}$: $\nexists cm$ such as $cm(P)$ is robust in $N$ faults, but the attacks can be made more difficult
- $\mathcal{S}$: even making the attack more difficult is not possible [Given-Wilson and Legay, 2020]

# The End

Thanks for watching

# Lazart architecture



# memcmps3 program

Listing: Analysis's main

```c
// main.c
#include "lazart.h"
#include "memcmps.h"

#define SIZE 4

int main()
{
    // Inputs
    uint8_t a1[SIZE];
    _LZ__SYM(a1, SIZE); // Symbolic array
    uint8_t a2[SIZE];
    _LZ__SYM(a2, SIZE); // Symbolic array

    bool equals = true;
    for(size_t i = 0; i < SIZE; ++i)
        if(a1[i] != a2[i])
            equals = false;
    _LZ__ORACLE(!equal); // Consider only
        different inputs

    BOOL res = memcmps(a1, a2, SIZE); // Call
        studied function

    _LZ__ORACLE(res == TRUE); // Attack
        objective
}
```

Listing: memcmps3 program

```c
// memcmps.h
typedef BOOL uint16_t;
#define TRUE    0x1234u
#define FALSE   0x5678u
#define MASK    0xABCDu

// memcmps.c
#include "memcmps.h"

BOOL memcmps(uint8_t* a, uint8_t* b, size_t len)
{
  BOOL result = FALSE;

  if (!memcmp(a, b, len)) {
    result ^= MASK;            // result = FALSE
      ^ MASK
    if (!memcmp(a, b, len)) {
      result ^= FALSE ^ TRUE; // result = MASK ^
          TRUE
      if (!memcmp(a, b, len)) {
        result ^= MASK;        // result = TRUE
      }
    }
  }

  return result;
}
```

# References I

de Ferrière, F. (2019).
A compiler approach to cyber-security.
2019 European LLVM developers' meeting.

Dureuil, L., Petiot, G., Potet, M., Le, T., Crohen, A., and de Choudens, P. (2016).
FISSC: A Fault Injection and Simulation Secure Collection.
In *Computer Safety, Reliability, and Security - 35th International Conference, SAFECOMP 2016, Trondheim, Norway, September 21-23, 2016, Proceedings*, pages 3–11.

Given-Wilson, T. and Legay, A. (2020).
Formalising fault injection and countermeasures.
In *Proceedings of the 15th International Conference on Availability, Reliability and Security*, pages 1–11.

Kim, C. H. and Quisquater, J.-J. (2007).
Fault attacks for crt based rsa: New attacks, new results, and new countermeasures.
In *IFIP International Workshop on Information Security Theory and Practices*, pages 215–228. Springer.

Lalande, J., Heydemann, K., and Berthomé, P. (2014).
Software countermeasures for control flow integrity of smart card C codes.
In *Pr. of the 19th European Symposium on Research in Computer Security, ESORICS 2014*, pages 200–218.

# References II


Natella, R., Cotroneo, D., and Madeira, H. S. (2016).
Assessing Dependability with Software Fault Injection: A Survey.
*ACM Computing Surveys*, 48(3):1–55.

Potet, M.-L., Mounier, L., Puys, M., and Dureuil, L. (2014).
Lazart: A symbolic approach for evaluation the robustness of secured codes against control flow injections.
In *2014 IEEE Seventh International Conference on Software Testing, Verification and Validation*, pages 213–222. IEEE.

Wookey/SSTIC20 (2020).
Inter-cesti: Methodological and technical feedbacks on hardware devices evaluations.
https://www.sstic.org/media/SSTIC2020/SSTIC-actes/inter-cesti_methodological_and_technical_feedbacks/SSTIC2020-Article-inter-cesti_methodological_and_technical_feedbacks_on_hardware_devices_evaluations-benadjila.pdf.