Tools for code and countermeasures analysis against multiple faults attacks

PhD Thesis defense

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Outline

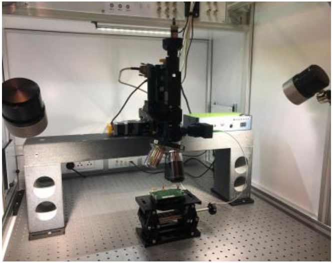
1. Context
2. The Lazart tool
3. Countermeasures placement
4. Countermeasures optimization
5. Conclusion and future work

Fault Injection

Fault-injection attacks

- Lasers
- Electromagnetic pulses
- Temperature
- Power & clock glitches
- Software induced

Figure: Laser fault injection bench [1]



Goal: modify device behavior/state to break security property and gain advantage

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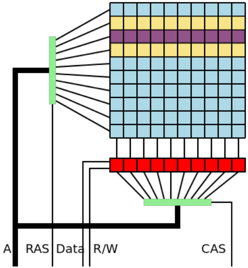
Figure: Rowhammer principle [2]



Goal: modify device behavior/state to break security property and gain advantage

verify_pin program

PIN verification program from FISSC [1] collection

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

    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;
}
```

- Compare user PIN against the card's one in constant time
- *Attack objective:* being authenticated with a false PIN

Faults injection - Example on `verify_pin`

PIN verification program from FISSC [1] collection

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

    return ret;
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- Fault model: modelisation of the faults to be injected

  → ex: **Test inversion**: inverse the branch taken during conditional branching

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    bool ret = true;
    size_t i = 0;
    for(; i < size; i++) // Fault
        if(a1[i] != a2[i])
            ret = false;

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

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

Faults injection - Example on `verify_pin`

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```c
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) {
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            // Authentication
            try_counter = 3;
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  multiples faults → countermeasures themselves can be attacked

Multiple Faults

State of the art attacks combine several faults to achieve their goal. Most robustness evaluation tools consider only single fault

- Need to help developer and auditor in multiple faults
- Standard analysis cannot be trivially applied
  → faults can induce modification in the CFG or the data flow

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Probl. 1

Need of automated tools to evaluate programs against multiple faults attacks

Robustness evaluation in multiple faults

- Comparing the robustness of different protected versions of a program is not trivial

  ⇒ *attack surface paradox [Dureuil 2016]*: countermeasure can add attack surface to the code

- How to count attacks in case of multiple faults ?

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  ⇒ Which program is the most secure ?

`verify_pin` version (from FISSC [1])	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 [2]

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Probl. 2

How to evaluate programs and countermeasures in multiple-fault context ?

Countermeasures evaluation challenge in multiple faults

- Try-and-error approaches are unsuitable for multi-faults

  → countermeasures themselves can be attacked

  → brute-forcing all countermeasures combinations is unrealistic

Probl. 3

How to help to place countermeasures and give guarantees on the protected program in multiple faults context ?

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Probl. 3

How to help to place countermeasures and give guarantees on the protected program in multiple faults context ?

- → most tools use systematic (everywhere) placement approach

Probl. 4

How to ensure that all added countermeasures are necessary ?

Contributions of this Thesis

Contributions:

- Extension of the tool Lazart and of robustness analysis for multiple faults

  → Problematic *P1*, *P2*

Problematics:

- *P1*: Multi-faults tools
- *P2*: Countermeasures evaluation / comparison
- *P3*: Countermeasures placement
- *P4*: Countermeasures necessity

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- Optimization of detector-based countermeasures

  → Problematic *P2*, *P4*

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Lazart

LAZART

Lazart [3] is an LLVM-level multi-fault robustness evaluation tool based on Dynamic-Symbolic Execution (KLEE)

→ Help developer to develop secure code

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- Support for fault models combination
- Fine description of fault space
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Fault models

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

→ cover most of high-level fault models

DSE and Fault Injection attacks

An *Injection Point* (IP) is mutated using a *symbolic boolean* determining if an injection occurs, forking execution into the nominal and faulted behavior

Listing: Nominal behavior

```
normal_behavior()
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Listing: Fault behavior

```
inject = symbolic_bool()
if inject and _fault_count <=
          _fault_limit:
     _fault_count++
     faulted_behavior()
else:
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Only faults (+ values) and some entries (user-defined) are symbolic

- Dynamic Symbolic Execution = Symbolic Execution + concretization

  → *correct* (except for some concretizations)

  → not guaranteed to be *complete* on path enumeration

→ Lazart tries to give as much information as possible (timeout, coverage, errors...)

Attack analysis - `verify_pin`

- Analysis parameters:
  - **Inputs**: Incorrect PIN
  - **Attack objective**: being authenticated with a false PIN
  - **Fault model**: up to N *test inversions*

Fault limit (N)	0	1	2	3	4
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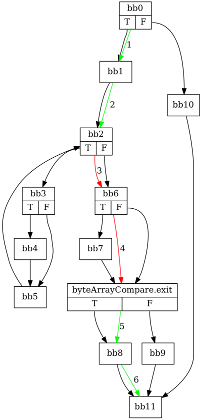
- A successful 2-order attack (right) inverts the loop's condition i < size and the later check if(i != size) killcard();

Figure: The 2-faults attack (Test Inversion)



CFG for 'verifyPIN' function

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→ How to simplify the attacks presented to the user in multiple faults ?

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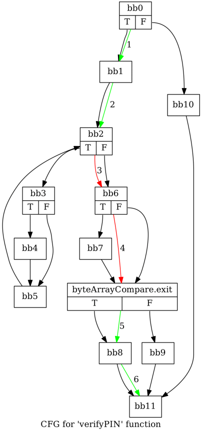


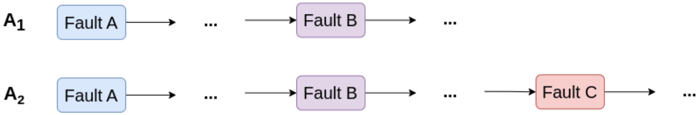
Redundancy / Equivalence

Attack traces are represented as a sequence of *nominal* and *faulted* transitions

- **Redundancy** and **equivalence** aims to filter attacks for the user in multiple faults

Definition (Redundancy prefix)

An attack a' is *redundant by prefix* wrt an attack a if the word of faulted transition of a is a **proper prefix** of the faulted transition word of a'



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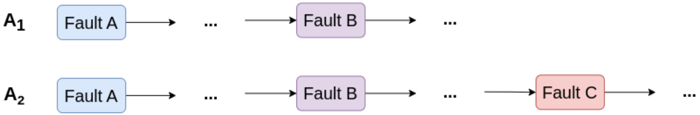

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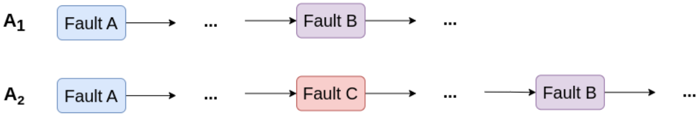

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Definition (Equivalence)

An attack *a* is **equivalent** to an attack a' if their sequence of transitions are equal

Definition (Fault-equivalence)

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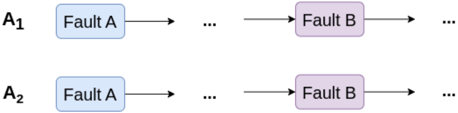

Experimentation

Tested programs:

- *Verify_PIN* (**vp**): smart-card PIN verification process

  ⇒ *model*: test inversion
- *RSA Cipher* (**rsa**): implementation of RSA encryption scheme.

  ⇒ *model*: data load mutation
- *Firmware Updater* (**fu**): updates a firmware from remote source

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- Simplifies the number of attacks to consider

  ⇒ by a factor 200 in a set of 15 examples from FISSC
- DSE is the main limit factor

  → with redundancy analysis matching on some examples

Table: Attack analysis on example programs

Program			Attacks					Minimal attacks (with equivalence)				
Nom	LoCs	IPs	1F	2F	3F	4F	Total	1F	2F	3F	4F	Total
vp0	25	4	12	21	18	7	**58**	3	0	0	0	**3**
vp4	45	11	34	118	180	147	**479**	3	0	1	0	**4**
vp7	78	8	4	36	116	173	**329**	1	2	0	0	**3**
rsa0	65	15	7	37	151	425	**620**	7	0	0	0	**7**
fu1	93	23	1	72	915	8191	**9179**	1	8	9	13	**31**
fu2	126	7	17	119	425	1031	**1592**	17	2	10	53	**82**

Summary

My contributions:

- **Python API :**
  - **Manipulation of traces, analysis and models**
  - **Fine fault space specification**
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  - **Switch to LLVM 9 (KLEE 2)**

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- **Combination of Lazart with static analysis (Frama-C) on Wookey boot loader [Lacombe 2023]**
- **Filed at APP**

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Placement of software countermeasures

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    size_t i = 0;
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        if(a1[i] != a2[i]) {
            ret = false;
        }
    }

    return ret;
}
```

- **Goal**: help to place countermeasures in multiple fault context (P2 and P3)

  → several fault models can be considered

  → countermeasures can be attacked with each fault model

  → countermeasures can introduce attacks

  → using a defined attack objective

Placement of software countermeasures

```
bool compare(uchar* a1, uchar* a2, size_t size)
{
    bool ret = true;
    size_t i = 0;
    for(; i < size; i++) {
        if(i >= size) killcard(); // Duplication (true)
        if(i >= size) killcard(); // Triplication (true)

        uchar a1_dup = a1[i];  // Load duplication
        if(a1_dup != a1[i]) killcard();
        uchar a2_dup = a2[i];  // Load duplication
        if(a1_dup != a1[i]) killcard();

        if(a1[i] != a2[i]) {
            if(i >= size)
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            ret = false;
        }
    }
    if(i != size) killcard(); // Duplication (false)
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    return ret;
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Placement of software countermeasures

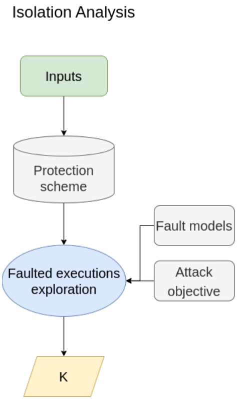
Goal: help to place countermeasures in multiple fault context

- Target robustness in *N* faults
- Give guarantees even if trace exploration is not complete
- Using a catalog of countermeasures schemes with *Injection Point* (IP) granularity

Approach:

- Compositional analysis using:
  - *Isolation analysis* of countermeasures schemes
    → Notion of protection coefficient
  - Exploration of attacks traces on the program P
- Placement algorithms

Principle of analysis in isolation



- Analysis of countermeasures scheme in isolation
- Focus on countermeasures with IP granularity

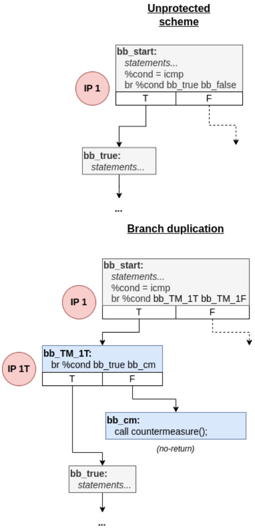
  → A **protection scheme** describe how an IP is protected
- Research of the *protection coefficient* (K) of the protection scheme:

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

  → Unprotected IP has a $K = 1$

  → Can be computed with Lazart

Analysis in isolation of Branch duplication scheme



Unprotected scheme

IP 1

```
bb_start:
  statements...
  %cond = icmp
  br %cond bb_true bb_false
T F

bb_true:
  statements...
...
```

Branch duplication

IP 1

```
bb_start:
  statements...
  %cond = icmp
  br %cond bb_TM_1T bb_TM_1F
T F
```

IP 1T

```
bb_TM_1T:
  br %cond bb_true bb_cm
T F

bb_cm:
  call countermeasure();
```

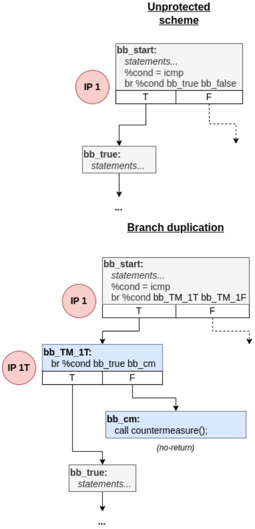
(no-return)

```
bb_true:
  statements...
...
```

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

Isolation analysis with *Branch Inversion* fault model

Analysis in isolation of Branch duplication scheme



Unprotected scheme

bb_start:
statements...
%cond = icmp
br %cond bb_true bb_false

bb_true:
statements...

...

Branch duplication

bb_start:
statements...
%cond = icmp
br %cond bb_TM_1T bb_TM_1F

bb_TM_1T:
br %cond bb_true bb_cm

bb_cm:
call countermeasure();

(no-return)

bb_true:
statements...

...

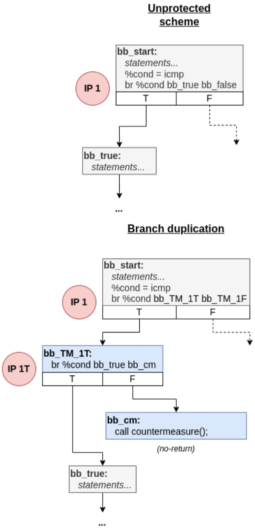
Branch Multiplication (BM_n): n-plication of a conditional branch

Isolation analysis with *Branch Inversion* fault model

Need to define:

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

Analysis in isolation of Branch duplication scheme



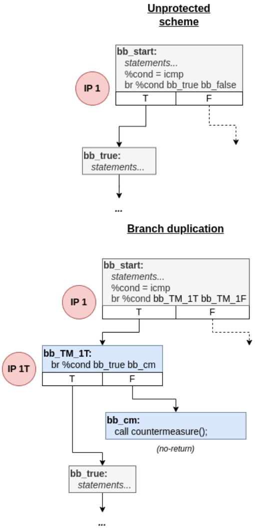
Branch Multiplication (BM_n): n-plication of a conditional branch

Isolation analysis with *Branch Inversion* fault model

Need to define:

- Input(s) of the scheme → **the %cond temporary**
- Output(s) of the scheme → **the destination branch**
- Entry point(s)
- Output point(s)
- Attack surface
- Nominal behavior

Analysis in isolation of Branch duplication scheme



Unprotected scheme

IP 1

bb_start:
statements...
%cond = icmp
br %cond bb_true bb_false

T F

bb_true:
statements...

...

Branch duplication

IP 1

bb_start:
statements...
%cond = icmp
br %cond bb_TM_1T bb_TM_1F

T F

IP 1T

bb_TM_1T:
br %cond bb_true bb_cm

T F

bb_cm:
call countermeasure();

(no-return)

bb_true:
statements...

...

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

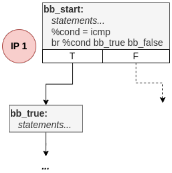
Isolation analysis with *Branch Inversion* fault model

Need to define:

- 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`)**
- Attack surface
- Nominal behavior

Analysis in isolation of Branch duplication scheme

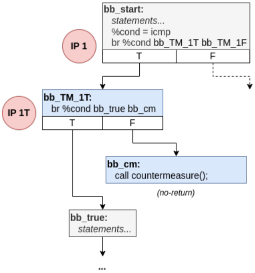
Unprotected scheme



bb_start:
statements...
%cond = icmp
br %cond bb_true bb_false

bb_true:
statements...

Branch duplication



bb_start:
statements...
%cond = icmp
br %cond bb_TM_1T bb_TM_1F

bb_TM_1T:
br %cond bb_true bb_cm

bb_cm:
call countermeasure();

(no-return)

bb_true:
statements...

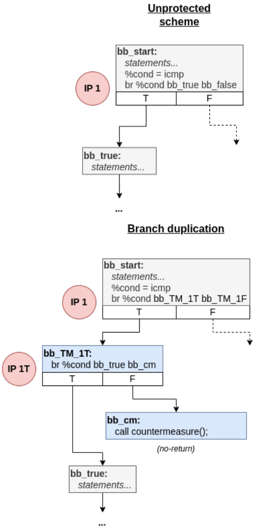
Branch Multiplication (BM_n): n-plication of a conditional branch

Isolation analysis with *Branch Inversion* fault model

Need to define:

- 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`)**
- Attack surface → ***IP* 1 and *IP* 1*T* with BI fault model**
- Nominal behavior

Analysis in isolation of Branch duplication scheme



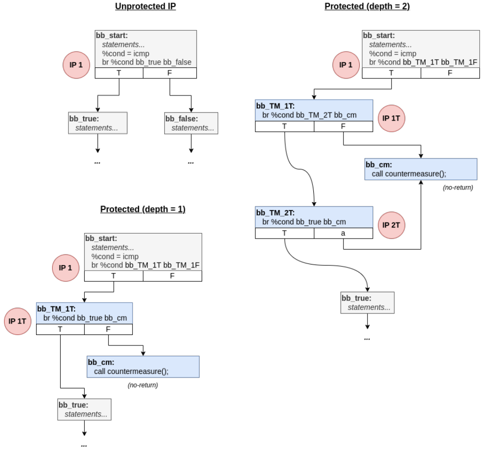
Branch Multiplication (BM_n): n-plication of a conditional branch

Isolation analysis with *Branch Inversion* fault model

Need to define:

- 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`**)**
- Attack surface → ***IP* 1 and *IP* 1*T* with BI fault model**
- Nominal behavior → **reach** `bb_true` **if and only if %cond is true**

Analysis in isolation of BM schemes



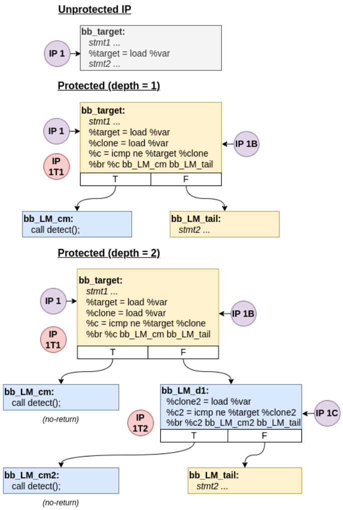
Branch Multiplication (BM_n): n-plication of a conditional branch

Isolation analysis with *Branch Inversion* fault model

Countermeasure	0-faults	1-fault	2-faults	3-faults	K
BM_0	0	1	0	0	**1**
BM_1	0	0	1	0	**2**
BM_2	0	0	0	1	**3**

Table: *BM* isolation analysis

Analysis in isolation of LM schemes



Unprotected IP

```
bb_target:
  stmt1 ...
  %target = load %var
  stmt2 ...
```

Protected (depth = 1)

```
bb_target:
  stmt1 ...
  %target = load %var
  %clone = load %var
  %c = icmp ne %target %clone
  %br %c bb_LM_cm bb_LM_tail
```

```
bb_LM_cm:
  call detect();
```

```
bb_LM_tail:
  stmt2 ...
```

Protected (depth = 2)

```
bb_target:
  stmt1 ...
  %target = load %var
  %clone = load %var
  %c = icmp ne %target %clone
  %br %c bb_LM_cm bb_LM_tail
```

```
bb_LM_cm:
  call detect();
```

(no-return)

```
bb_LM_d1:
  %clone2 = load %var
  %c2 = icmp ne %target %clone2
  %br %c2 bb_LM_cm2 bb_LM_tail
```

```
bb_LM_cm2:
  call detect();
```

(no-return)

```
bb_LM_tail:
  stmt2 ...
```

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	K
LM_0	0	1	0	0	**1**
LM_1	0	0	1	0	**2**
LM_2	0	0	0	1	**3**

Table: *LM* isolation analysis

Placement algorithms principles

GOAL: generate a P' program which is robust to *N* faults

⇒ Give guarantees that P' is *more robust than P* even if trace set is *incomplete* or if catalog is incomplete

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Basic structure of placement algorithms:

1. Obtain set of attack traces

   ⇒ Computed with all fault models and the user-defined attack objectives
2. Compute **required protection coefficient** (K_{ip}) for each IP (initialized to 1)
3. Generate P' with protection scheme matching the **required protection coefficients**

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

Placement algorithms principles

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3. Generate P' with protection scheme matching the **required protection coefficients**

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

Three approaches:

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

Systematic placement algorithms

```
def placement_min(C: Catalog, P: Program, M: AttackModel, n: int):
    # Get sucessfull non-detected attacks.
    attacks = T_s(P, M, n)
    # Filter with minimals attacks.
    minimals = RedundacyAnalysis(attacks).minimals()

    # Initial protection factors Kn at 1 for all IP.
    required_kn = { IPA: 1, IPB: 1, ..., IPN: 1 }

    # Apply ponderation of n for all IP in traces
    for attack in minimals:
        for IP in attack:
            required_kn[IP] = n + 1 # Make IP robust en n faults.

    # Generation of P’
    P‘ = P
    for IP, kn in required_kn:
        S = C.get_cm(IP.model(), kn) # Select protection scheme from catalog
        P‘ = S(P‘, IP) # Apply local protection
    return P‘
```

Systematic algorithms:

- Naive placement (`naive`): protect all IP with K > N

  → *corresponds to standards systematic protection tools*

  → do not require attacks paths
- Attack placement (`atk`): protect all IP in attacks with K > N
- Minimal placement (`min`) (**on left)**: protect all IP in minimal attacks with K > N

Systematic placement algorithms

```
def placement_min(C: Catalog, P: Program, M: AttackModel, n: int):
    # Get sucessfull non-detected attacks.
    attacks = T_s(P, M, n)
    # Filter with minimals attacks.
    minimals = RedundacyAnalysis(attacks).minimals()

    # Initial protection factors Kn at 1 for all IP.
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    # Apply ponderation of n for all IP in traces
    for attack in minimals:
        for IP in attack:
            required_kn[IP] = n + 1 # Make IP robust en n faults.

    # Generation of P’
    P‘ = P
    for IP, kn in required_kn:
        S = C.get_cm(IP.model(), kn) # Select protection scheme from catalog
        P‘ = S(P‘, IP) # Apply local protection
    return P‘
```

Systematic algorithms:

- Naive placement (`naive`): protect all IP with K > N

  → *corresponds to standards systematic protection tools*

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- Attack placement (`atk`): protect all IP in attacks with K > N
- Minimal placement (`min`) (**on left)**: protect all IP in minimal attacks with K > N

Guarantees:

- **Robust in *N* faults** if the catalog provides required *K* for each IP (complete catalog) and if the entry trace set is complete

Systematic placement algorithms

```
def placement_min(C: Catalog, P: Program, M: AttackModel, n: int):
    # Get sucessfull non-detected attacks.
    attacks = T_s(P, M, n)
    # Filter with minimals attacks.
    minimals = RedundacyAnalysis(attacks).minimals()

    # Initial protection factors Kn at 1 for all IP.
    required_kn = { IPA: 1, IPB: 1, ..., IPN: 1 }

    # Apply ponderation of n for all IP in traces
    for attack in minimals:
        for IP in attack:
            required_kn[IP] = n + 1 # Make IP robust en n faults.

    # Generation of P’
    P‘ = P
    for IP, kn in required_kn:
        S = C.get_cm(IP.model(), kn) # Select protection scheme from catalog
        P‘ = S(P‘, IP) # Apply local protection
    return P‘
```

Systematic algorithms:

- Naive placement (`naive`): protect all IP with K > N

  → *corresponds to standards systematic protection tools*

  → do not require attacks paths
- Attack placement (`atk`): protect all IP in attacks with K > N
- Minimal placement (`min`) **(on left)**: protect all IP in minimal attacks with K > N

Guarantees:

- **Robust in *N* faults** if the catalog provides required *K* for each IP (complete catalog) and if the entry trace set is complete
- **At least as robust as** *P* otherwise

  → if the catalog is incomplete, *vulnerable traces in P' are known*

Block placement algorithm

```
def placement_bloc_h(C: Catalog, P: Program, M: AttackModel, n: int):
    # Get sucessfull non-detected attacks.
    attacks = T_s(P, M, n)
    # Filter with minimals attacks.
    minimals = RedundacyAnalysis(attacks).minimals()

    # Initial protection factors Kn at 1 for all IP.
    required_kn = { IPA: 1, IPB: 1, ..., IPN: 1 }

    # For all attacks by faults count.
    for order in 1 to n:
        # Loop trought order-faults attacks by number of associated redundant attacks.
        for attack in minimals.where(order=order).sort_by(Minimals):
            if is_protected(attack, required_kn):
                continue
            # Make attack robust in n faults
            IP = select IP in attack with most occurence
            required_kn[IP] = n + 1

    # Generation of P’
    P‘ = P
    for IP, kn in required_kn:
        S = C.get_cm(IP.model(), kn) # Select protection scheme from catalog
        P‘ = S(P‘, IP) # Apply local protection
    return P‘
```

Protection of at least one IP per minimal attack with K > N

→ heuristic based

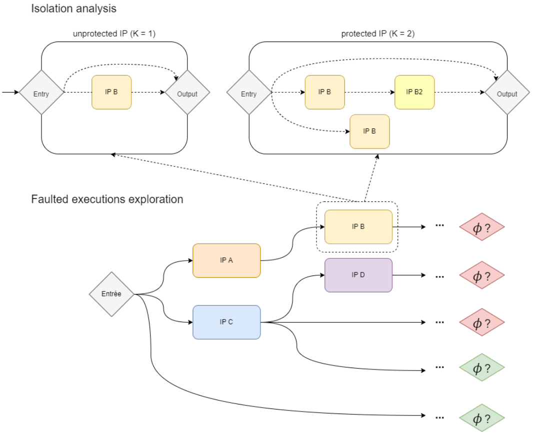
Guarantees:

- **Robust in *N* faults** if the catalog provides required *K* for each IP (complete catalog) and if the entry trace set is complete
- **At least as robust as** *P* otherwise

  → if the catalog is incomplete, *vulnerable traces in P' are known*

How to be sure than no attack paths is introduced by non-protected IPs ?

Compositional analysis placement

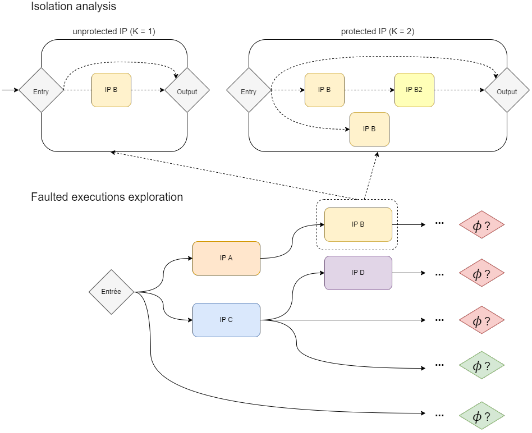


- Isolation analysis for each considered protection scheme with all studied fault models

- Attacks traces gives guarantees on which IP violation can lead to an attack

  → *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

  → *Here, IPA can be left unprotected if IPB is protected*

⇒ **Protection can be distributed between the IPs**

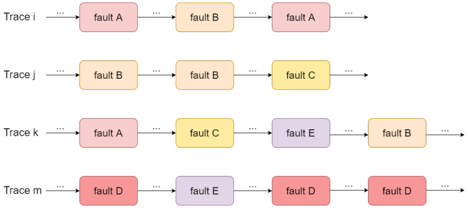
Optimal distributed placement

- Distribute protections of IPs inside minimal attacks traces to ensure at least N + 1 faults are required to obtain attacks

  → usable if the catalog $\mathcal{C}$ does not contains CM for K > N

- An Integer Linear Programming (ILP) optimization problem

  → attacks gives constraints on the protection to apply



$C_i = 2x_a + x_b \geq N + 1$

$C_j = 2x_b + x_c \geq N + 1$

$C_k = x_a + x_b + x_c + x_e \geq N + 1$

$C_m = 3x_d + x_e \geq N + 1$

Research of the **optimal** placement

⇒ 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

  → *guarantees on partially protected IPs*

Optimal distributed placement

```
1   def placement_rep_opt(C: Catalog, P: Program, M:
        AttackModel, n: int):
2       # Get sucessfull non-detected attacks.
3       attacks = T_s(P, M, n)
4       # Filter with minimals attacks.
5       minimals = RedundacyAnalysis(attacks).
          minimals()
6
7       # Initial protection factors Kn at 1 for all
           IP.
8       required_kn = { IPA: 1, IPB: 1, ..., IPN: 1
          }
9
10      constraints = [] # constraints for ILP
11      for attack in minimals:
12          constraints += compute_constraint(attack
          )
13
14      required_kn = solve_ilp(constraints,
          required_kn)
15
16      # Generation of P’
17      P‘ = P
18      for IP, kn in required_kn:
19          S = C.get_cm(IP.model(), kn) # Select
          protection scheme from catalog
20          P‘ = S(P‘, IP) # Apply local protection
21      return P‘
```

Optimal placement using ILP problem encoding:

1. Encode constraints from attack traces (lines 10-12)
2. Solve ILP (line 14)
3. Generate P’ (lines 17-20)

Guarantees:

- **Robust in *N* faults** if the catalog provides required *K* for each IP (complete catalog) and if the entry trace set is complete

  → and **optimal** (i.e. minimal set of protections wrt $\mathcal{C}$)
- **At least as robust as** *P* otherwise

  → if the catalog is incomplete, *vulnerable traces in P' are known*

Experimentation - verify_pin

verify_pin [1] (**VP**): smart-card PIN verification process

- *fault model:* branch inversion
- *inputs:* input PINs are different and symbolic
- *attack objective:* being authenticated or do not decrement the try counter
- *countermeasures:*
  - *integrated:* hardened boolean, fixed time loop
  - *placement:* branch multiplication (BM)

Exp.			Algo.	$\sum$ of protections				Robust
Program	Fault Model	IPs		1-fault	2-faults	3-faults	4-faults	
`vp2b`	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 - FU1

firmware_updater v1 (**fu1**): updates a firmware from remote source

- *fault model:* branch inversion + data load
- *inputs:* input PINs are different and symbolic
- *attack objective:* load a corrupted firmware or avoid load
- *countermeasures:*
  - *integrated:* systematic tests duplication
  - *placement:* 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**	✓

Summary

- Robustness of placement depend 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

  → if not, attack traces on P' are known

  → more robust than P even if trace set is incomplete

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

  → Optimal placement is guaranteed with ILP

Algorithme	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)

  → even with optimal algorithm and ILP (1-fault attacks)

Outline

1. Context

2. The Lazart tool

3. Countermeasures placement

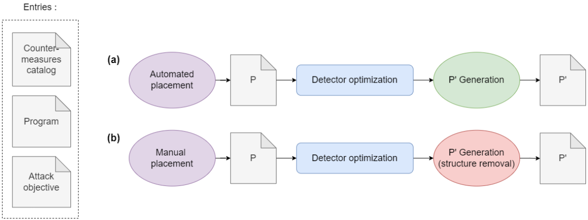
4. Countermeasures optimization

5. Conclusion and future work

Countermeasures optimization approach

- Can some part of the countermeasure be removed without adding new attacks ?

  ⇒ Probl. P2 & P4



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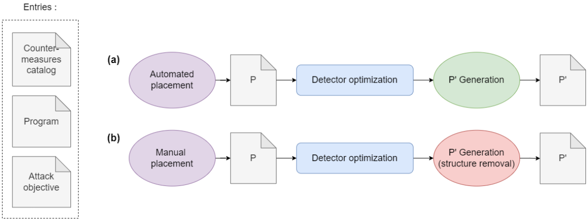

- **Approach:**

  ⇒ focus on the subclass of detector-based countermeasures

  ⇒ based on the execution with non-blocking detectors

Definitions - Detectors and bodies

We divide a **detector-based countermeasure** in two parts:

- Detectors are control point in the program corresponding to sanity checks about the current state
- The countermeasure's bodies: shadow variables, parameters, additional computation etc.

```
bool compare(uchar* a1, uchar* a2,
    size_t size, size_t size_dup) {
    size_t i = 0u;
    bool result = true;
    bool result_dup = true;

    for(; i < size; i++) {
        if(a1[i] != a2[i])
            result = false;
        if(a1[i] != a2[i])
            result_dup = false;

        if(result != result_dup)
            countermeasure();
    }

    if(i != size)
        countermeasure();
    if(i != size_dup)
        countermeasure();

    return result;
}
```

Objectives:

- determine if some detector could be removed, without adding any attack paths for the considered attack model.

Definitions - Detectors and bodies

We divide a **detector-based countermeasure** in two parts:

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Examples

- *Test duplication* (**TD**)
- *Load Multiplication* (**LM**)
- *SecSwift Control Flow* (**SSCF**)[4]: associates an unique identifier to each basic block and uses a xor-based mechanism to ensure that the correct branch has been taken
- **LBH** [2]: introduce step counters to protect against C-level instruction skips. Each counter verification is a `detector`

```
bool compare(uchar* a1, uchar* a2,
    size_t size, size_t size_dup) {
    size_t i = 0u;
    bool result = true;
    bool result_dup = true;

    for(; i < size; i++) {
        if(a1[i] != a2[i])
            result = false;
        if(a1[i] != a2[i])
            result_dup = false;

        if(result != result_dup)
            countermeasure();
    }

    if(i != size)
        countermeasure();
    if(i != size_dup)
        countermeasure();

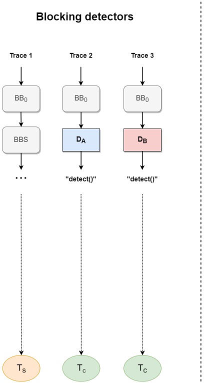
    return result;
}
```

Objectives:

- determine if some detector could be removed, without adding any attack paths for the considered attack model.

Countermeasure optimization - Idea: don’t stop execution after detection

- Detector are considered as a structure `if(cond) killcard();` that can be attacked and `killcard` an atomic detection function

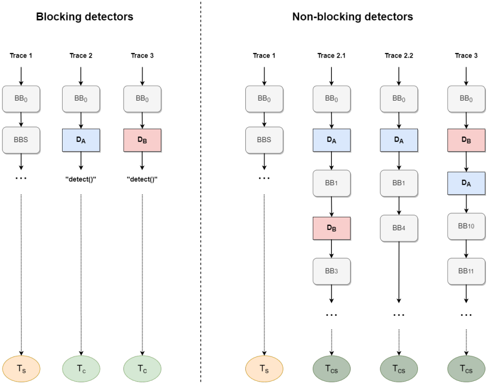


Countermeasure optimization - Idea: don't stop execution after detection

- Detector are considered as a structure `if(cond) killcard();` that can be attacked and `killcard` an atomic detection function
- *Intuition:* Explore the program executions by noting at each detector location if the corresponding detector would be triggered

  ⇒ all variation of detectors are considered in one single exploration.

  ⇒ require side-effect free property on detectors



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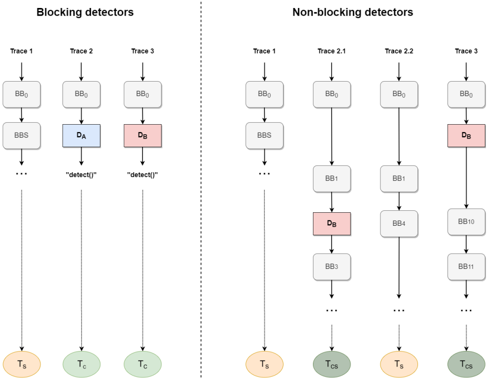

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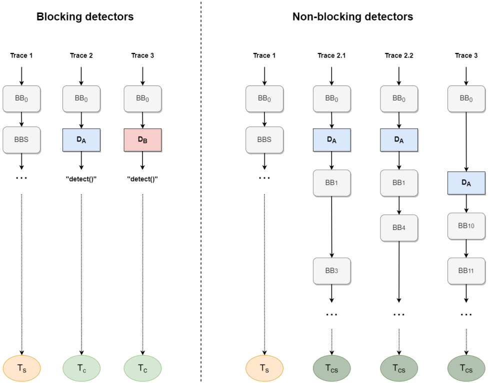

Countermeasure optimization - Principle

- **An optimization problem:** Search the minimal set of detectors $\mathcal{D}$ such as at least one detector cover each trace of the set of detected attack traces

  $\Rightarrow$ using non-blocking detectors

- Exploration space can be reduced by *classification* step:
  - If $\forall t \in T'$, $d_i \notin \{cm(t)\}$, d_i is **inactive** (should be removed)
  - If $\exists t \in T'$, $cm(t) = \{d_i\}$, d_i is **necessary** (should be kept)
  - Other detectors are **repetitive**
    $\Rightarrow$ focus on traces containing only **repetitive** detectors

Methodology - Step 1 - Test Duplication results in 2 faults

VerifyPIN + Test Duplication:

- 86 traces in 2 faults with **Lazart**

Table: Detectors classification in 2 faults

Detector	0	1	2	3	4	5	6	7	8	9	100
Class	R	I	R	R	R	R	R	R	N	I	N

```
bool verify_pin(uchar* user_pin) {
    if(try_counter > 0)      D0 & D1
        if(compare(user_pin, card_pin, PIN_SIZE)
              ) {  D8
            try_counter = 3;
            return true;
        } else {  D9
            try_counter--;
            return false;
        }
    return false;
}
```

```
bool compare(uchar* a1, uchar* a2, size_t size)
      {
    bool result = true;
    size_t i = 0;
    for(; i < size; i++) {  D2 & D3
        if(a1[i] != a2[i]) {  D4 & D5
            result = false;
        }
    }

    if(i != size)  D6 & D7
        countermeasure(100);  D100

    return result;
}
```

Step 4 - Removed CCPs for verifyPIN (2 faults)

The removed and kept detectors and bodies for *Test duplication* on `verify_pin` with 2 faults

```
bool verify_pin(uchar* user_pin) {
    bool c_1;
    bool c_2;
    if(c_1 = try_counter > 0) {
        if(!c_1)
            killcard();

        if(c_2 = compare(user_pin, card_pin, PIN_SIZE)) {
            if(!c_2)
                countermeasure();
            try_counter = 3;
            return true;
        } else {
            if(c_2)
                countermeasure();
            try_counter--;
            return false;
        }
    } else
        if(c_1)
            countermeasure();

    return false;
}
```

```
bool compare(uchar* a1, uchar* a2, size_t size) {
    bool result = true;
    size_t i = 0;
    bool c_1;
    bool c_2;
    bool c_3;

    for(; c_1 = i < size; i++) {
        if(!c_1)
            countermeasure();
        if(c_2 = a1[i] != a2[i]) {
            if(!c_2)
                countermeasure();
            result = false;
        } else
            if(c_2)
                countermeasure();
    }
    if(c_1)
        countermeasure();

    if(c_3 = i != size) {
        if(!c_3)
            countermeasure();
        countermeasure();

    } else
        if(c_3)
           countermeasure();

    return result;
}
```

Experimentations

Program	Detectors	1 attack	2 attacks	3 attacks
VP + TD	11	72%	63%	18%
VP + SSCF	13	92%	76%	23%
VP + LBH	31	93%	93%	32%
FU + TD	14	0%	0%	0%
FU + SSCF	24	12%	12%	8%
GC1 + TD	39	37%	34%	34%
GC1 + SSCF	38	57%	28%	28%
AES RK + TD	2	50%	50%	0%
AES RK + SSCF	3	66%	33%	0%
AES C + TD	8	50%	50%	0%
AES C + SSCF	13	76%	61%	38%

Three countermeasures experimented:

- *Test duplication* (**TD**): presented previously
- *SecSwift Control Flow* (**SSCF**)[4]: associates an unique identifier to each basic block and uses a xor-based mechanism to ensure that the correct branch has been taken
- **LBH** [2]: introduce step counters to protect against C-level instruction skips. Each counter verification is a `detector`

Outline

1. Context

2. The Lazart tool

3. Countermeasures placement

4. Countermeasures optimization

5. Conclusion and future work

Conclusion

Robustness evaluation with Lazart

- filter of multi-fault attacks: equivalence and redundancy
- combination of fault models
- user accessibility, case studies

Countermeasures evaluation

- isolation analysis
- placement algorithms

  → gives strong guarantees, even if the trace set is incomplete

  → allows combination of fault model in multiple faults
- detector optimization algorithm

  → up to 80% of `detectors` removed

Publications:

- *Combining Static Analysis and Dynamic Symbolic Execution in a Toolchain to detect Fault Injection Vulnerabilities*
  Guilhem Lacombe, David Féliot, Etienne Boespflug and Marie-Laure Potet, *Journal of Cryptography Engineering 2023*
- *Combining Static Analysis and Dynamic Symbolic Execution in a Toolchain to detect Fault Injection Vulnerabilities*
  Guilhem Lacombe, David Féliot, Etienne Boespflug and Marie-Laure Potet, *PROOFS Workshop 2021*
- *Countermeasures Optimization in Multiple Fault-Injection Context*
  Etienne Boespflug, Cristian Ene, Marie-Laure Potet and Laurent Mouniter, *FDTC 2020*

Future Works

Tools:

- Extension of fault models in Lazart
- Extension of automated countermeasures in Lazart
- Validate contribution on more example programs
- Combination with static analysis
- "fault-aware" dynamic-symbolic execution engine

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Countermeasure placement:

- Study of countermeasures without IP granularity
- Study of countermeasures propagating states (SSCF, Swift...)

  → may require to consider two isolation analysis cases: sane CM's inputs and corrupted CM's inputs
- Study of more complex CFG fault models

  → requires to take into account the several entry and output points of the protection scheme
- Extension of notion of *adequation*, *perfection* of CMs and *protectability* of fault models

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Countermeasure optimization:

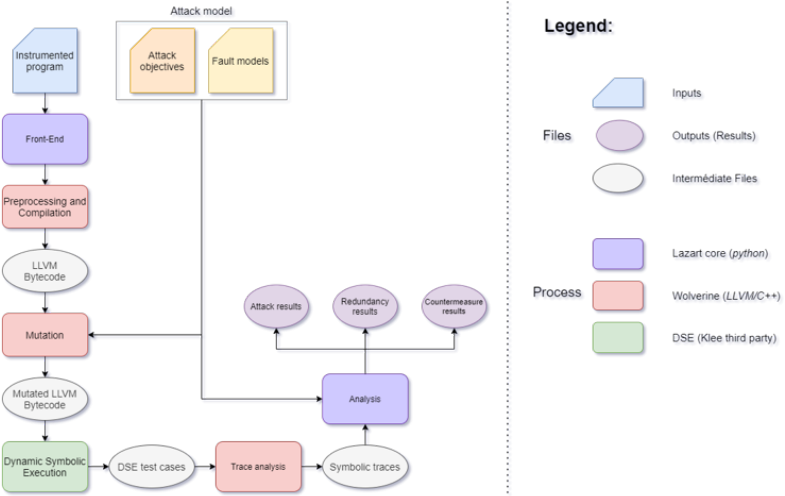
- Switch to Lazart 4
- Fully symbolic version (relax constraints on detectors)

  $\longrightarrow$ internal states may be difficult to consider
- Study of other countermeasures

The End

Thanks for watching

Lazart architecture



Attack model

Attack objectives

Fault models

Instrumented program

Front-End

Preprocessing and Compilation

LLVM Bytecode

Mutation

Mutated LLVM Bytecode

Dynamic Symbolic Execution

DSE test cases

Trace analysis

Symbolic traces

Analysis

Attack results

Redundancy results

Countermeasure results

Legend:

Files

Inputs

Outputs (Results)

Intermédiate Files

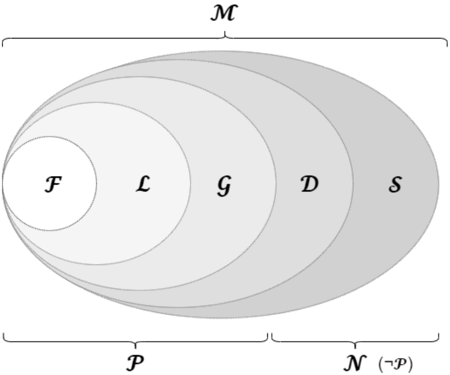
Process

Lazart core (*python*)

Wolverine (*LLVM/C++*)

DSE (Klee third party)

Model protectability



Modèles:

- $\mathcal{P}$: Protégeables
  - $\mathcal{F}$: Parfaitement protégeables
  - $\mathcal{L}$: Localement protégeables
  - $\mathcal{G}$: Globalement protégeables
- $\mathcal{N}$: Non-protégeables
  - $\mathcal{D}$: Diluables
  - $\mathcal{S}$: Strictement non-protégeables

- notion of *adequation* of CMs
- notion of *perfection* of CMs
- notion of protectability of models

Future work - Fully symbolic CCPO

- The methodology requires properties for detectors → a full symbolic version can be used

- Each detectors forks the execution:

```
if(sym_bool()) // Is the detector active ?
{
    // Local code with detector
}
else
{
    // Local unprotected code.
}
```

- Issues:
  - Paths explosion
  - Some countermeasure structures depend on the presence of detectors (can require specific instrumentation for CMs)

Detector requirements

Let V_P be the state of the non-protected program and V_C the state of the countermeasures.

The detector has limitation for the read and write operation on the states V_P et V_C.

Listing: Generic detector example

```
...
stm1; // can: read(VP, VC) & write(VP, VC)

// Detector:
if(cond) { // read(VP, VC)
    stm2; // read(VP, VC) & write(VP, VC)
    killcard();
}

stm3; // read(VP, VC) & write(VP, VC)
...
```

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;
}
```

memcmps3 analysis file

```
#!/usr/bin/python3
from lazart.lazart import *

attack_model = functions_list(["memcmps"], [ti_model(), data_model({ "vars": { "result": "
      __sym__", "len":  "__sym__" } })])

a = Analysis(["memcmps.c", "main.c"], # Input files
    attack_model, # Attack model
    flags=AnalysisFlag.AttacksAnalysis, # Analysis type
    compiler_args="-Wall",
    max_order=4,
    path="my_analysis")

execute(a)

```

Listing: memcmps3 program

Countermeasure optimization

- The program P contains a set of *detector* $\mathcal{D}$.

  Stopping traces: $s_0 \dots s_n d_i$, where s_i are nominal or faulty transitions, and d_i the triggered detector

  Non-stopping traces: $s_0 \dots s_n d_i s_0^2 \dots s_n^2 d_j \dots$ with d_i detectors triggering

  $\rightarrow$ Stopping traces are prefix of non-stopping ones. One stopping trace can lead to several non-stopping traces

- **Goal** $\Rightarrow$ find the minimal set of detectors in which at least one detector is kept for each trace

- Only traces which validate the attack objective ϕ and in which at least one detector is triggered are considered. This trace set is denoted $\mathcal{T}_P$.

  The detector *selection* is an optimization problem, searching a minimal set of detectors covering each traces of $\mathcal{T}_P$ with at least one trigger.

  Exploration space can be reduced:

  - If $\forall t \in T', d_i \notin \{\mathit{triggered}(t)\}$, d_i is inactive (should be removed)
  - If $\exists t \in T', \mathit{triggered}(t) = \{d_i\}$, d_i is necessary (should be kept)

Experimentation results - Playing with the attack objectives

The **attack objective** strongly impacts the removed **detectors**.

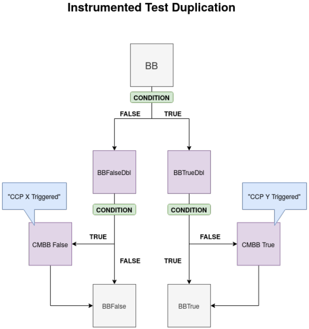
- ϕ_{auth}: being authenticated with a false PIN.
- ϕ_{ptc}: do not decrement the try counter with a false PIN.

Table: Removed detectors depending on attack objective (VP + TD)

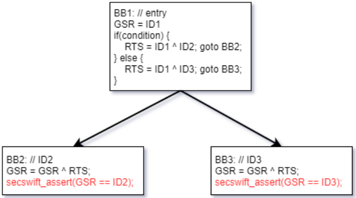
Property	1 fault	2 faults	3 faults
ϕ_{auth}	83%	72%	18%
ϕ_{ptc}	72%	63%	9%
$\phi_{auth \wedge ptc}$	83%	72%	18%
$\phi_{auth \vee ptc}$	72%	63%	9%
ϕ_{true}	18%	9%	9%

Test Duplication

The *Test Duplication* generate two detectors for each conditional branch.



SecSwift Control-Flow



```
BB1: // entry
GSR = ID1
if(condition) {
    RTS = ID1 ^ ID2; goto BB2;
} else {
    RTS = ID1 ^ ID3; goto BB3;
}
```

```
BB2: // ID2
GSR = GSR ^ RTS;
secswift_assert(GSR == ID2);
```

```
BB3: // ID3
GSR = GSR ^ RTS;
secswift_assert(GSR == ID3);
```

SecSwift ControlFlow is one of the 3 parts of SecSwift[4]

- Designed for Control-Flow Integrity (CFI)
- Uses static signature for each basic block and propagate errors
- Each secswift_assert is a **detector**

LBH’s countermeasure [2]

```
#define INCR(cnt,val)  cnt = cnt + 1;
#define CHECK_INCR(cnt,val, cm_id) if(cnt != val) countermeasure(cm_id); \
    cnt = cnt + 1;
[...]


BOOL verifyPIN(unsigned short* CNT_0_VP_1)
{
    CHECK_INCR(*CNT_0_VP_1, CNT_INIT_VP + 0, 0LL)
    g_authenticated = 0;
    CHECK_INCR(*CNT_0_VP_1, CNT_INIT_VP + 1, 1LL)
    DECL_INIT(CNT_0_byteArrayCompare_CALLNB_1, CNT_INIT_BAC)
    CHECK_INCR(*CNT_0_VP_1, CNT_INIT_VP + 2, 2LL)
    BOOL res = byteArrayCompare(g_userPin, g_cardPin, PIN_SIZE, &CNT_0_byteArrayCompare_CALLNB_1);
[...]
```

- Insert *step-counters* for each C construct
- *Checking macros* (such as `CHECK_INCR`) are **detectors**
- Analysis allows to know where the counter verification can be removed

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