The Lazart tool - multiple faults attacks and DSE

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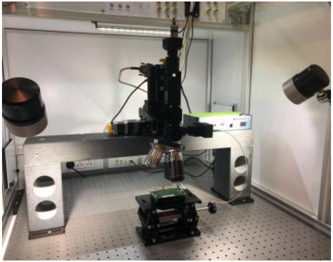
Outline

Fault Injection

Fault-injection attacks

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

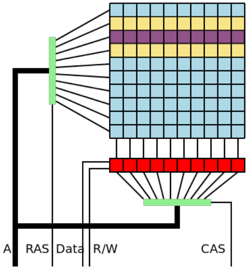
Figure: Laser fault injection bench [1]



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

Fault Injection

Figure: Rowhammer principle [2]



Fault-injection attacks

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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;
}

bool verify_pin(uchar* user_pin) {
    if(try_counter > 0)
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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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    for(; i < size; i++) // Fault
        if(a1[i] != a2[i])
            ret = false;

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

    return ret;
}

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

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

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  multiples faults → countermeasures themselves can be attacked

Robustness evaluation in multiple faults

State of the art attacks combine several faults to achieve their goal. [2, 3, 4]

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Robustness evaluation in multiple faults

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- Comparing the robustness of different protected versions of a program is not trivial
  $\Rightarrow$ *attack surface paradox [Dureuil 2016]*: countermeasure can add attack surface to the code
- How to count attacks in case of multiple faults ?
  $\Rightarrow$ 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 [5]

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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
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Low-Level Virtual Machine (LLVM)

LLVM [6] is an intermediate representation commonly used for compilers (clang, rustc, Swift, Julia...), analysis tools (KLEE, AdressSanitizer...) and other projects (Unity with Burst).

Properties

- Infinite number of register (called *temporaries*
- Generic and typed assembly language
- Single Static Assignment (SSA) form [**?**]
- LLVM-IR used in binary and textual form between optimisation / analysis pass

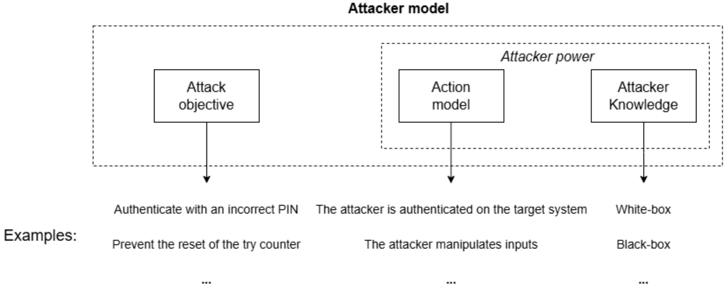
Listing: *Hello World!* program in IR LLVM (LLVM-9)

```
@.str = private unnamed_addr constant [14 x i8] c"Hello world !\00", align 1

define dso_local i32 @main(i32 %0, i8** %1) {
  %3 = alloca i32, align 4
  %4 = alloca i32, align 4
  %5 = alloca i8**, align 8
  store i32 0, i32* %3, align 4
  store i32 %0, i32* %4, align 4
  store i8** %1, i8*** %5, align 8
  %6 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds ([14 x i8], [14 x i8]* @.str, i64 0, i64 0))
  ret i32 0
}

declare dso_local i32 @printf(i8*, ...)
```

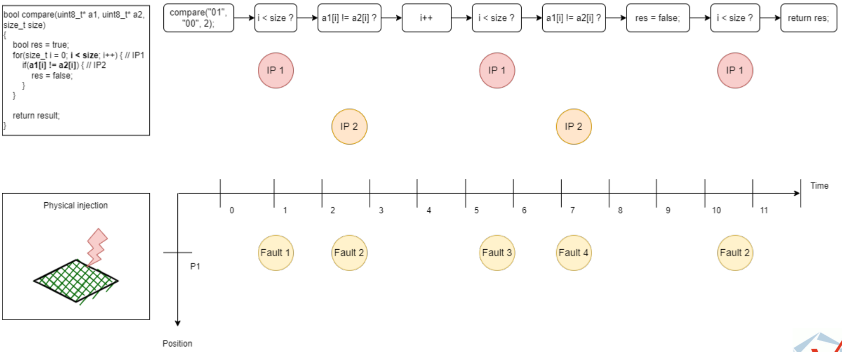
Attack model and representation level



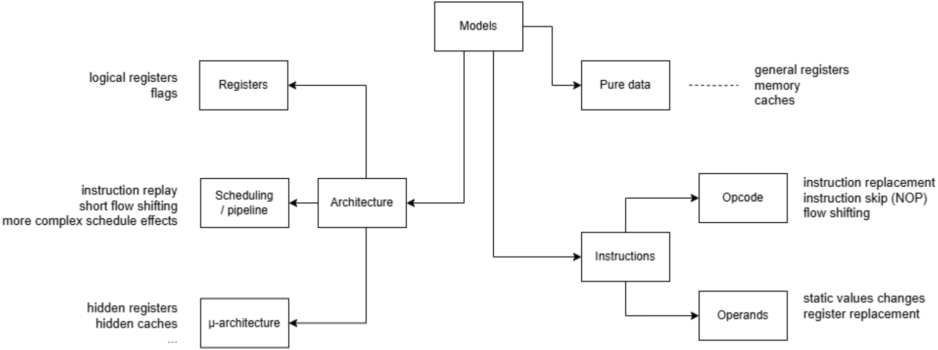
Attack model and representation level

Attacker model strongly depends on representation level.

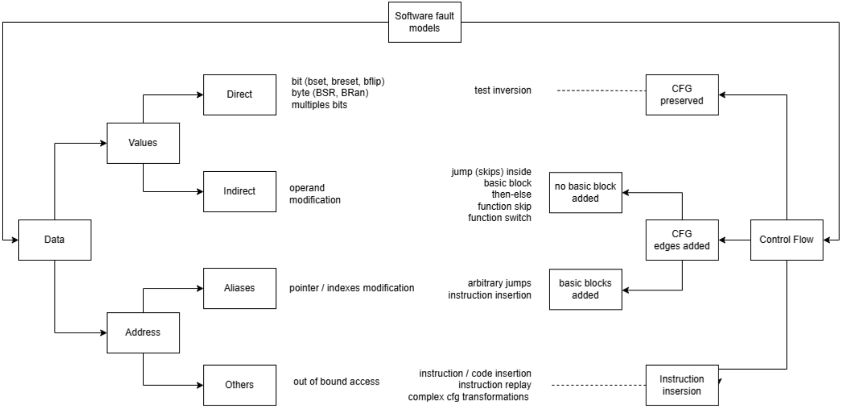
- Comparison of a faulted execution on software-level and physical-level:



Binary/architectural fault models



Software fault models



Faults Models and exploitation

Binary level effects:

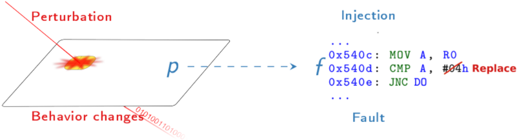
- Opcode / Operand replacement [7]
- Data modification: register or memory mutation [8, 9]
- Instruction replay [10]
- Out of ISA effects [11]

Software level effects:

- Control Flow modification [12, 4]
- Call graph modification [4]
- Variables / address alteration [5]

Exploitation:

- Side-channel [13]
- Bypassing secure boots [14]
- Privilege escalation [15]
- Buffer overflow [4]



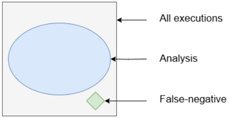
⇒ Combining several fault from different fault level allows to create more complex fault models.

Outline

Code analysis approaches

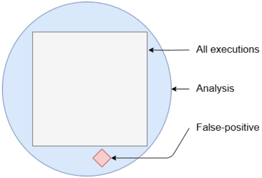
Under-approximation methods

examples: fuzzing, symbolic execution, unit tests...



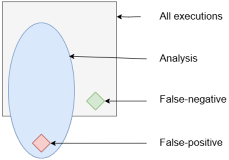
Over-approximation methods

examples: abstract interpretation



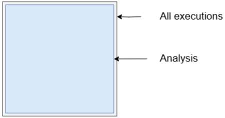
Hybrids methods

examples: dynamic-symbolic execution



Exact methods

examples: formal proofs



Dynamic Symbolic Execution

Formal method based on execution of the program using *symbolic* variables

Listing: Function `example`

```
void example(int x, int y) {
        σ = { x → x0, y → y0 }
        PC0 ≡ true
    if (x + y > 2) {   PC1 ≡ x0 + y0 > 2
        z = 2*x + y;
                σ = {z → 2*x0 + y0, x → x0, y → y0 }
        if (z == 20) {
                PC2 ≡ x0 + y0 > 2 ∧ 2 * x0 + y0 = 20
            x = z + 3;
                σ = { z → 2 * x0 + y0, x →
                2 * x0 + y0 + 3, y → y0 }
            print(x);
        }
        else {  PC3 ≡ x0 + y0 > 2 ∧ 2 * x0 + y0 ≠ 20
            y *= 2;           σ = { z →
                2 * x0 + y0, x → x0, y → 2 * y0 }
            assert(x != 0);
        }
    }
    else {  PC4 ≡ x0 + y0 <= 2
        foo();
    }
}
```

- Variables can be evaluated symbolicaly, maintaining a symbolic memory state σ
- Each time a condition is encountered, the execution is forked with the Path Constraint (PC) updated

  $\rightarrow$ a SMT solver is called to check if the PC of the path is satisfiable

Find entry that trigger the assert (x != 0) $\rightarrow$ solve the PC: [5, 10]

DSE and Fault Injection attacks

Definition (Godefroid 2011)

A path constraint PC_ω is *correct* if every model satisfying PC_ω gives entries for an execution following the path ω.
A path constraints PC_ω is *complete* if every entries following the path ω is a model satisfying PC_ω.

Listing: Nominal behavior

```
normal_behavior()
```

Listing: Faulted behavior

```
inject = symbolic_bool()
if inject and _fault_count <=
        _fault_limit:
    _fault_count++
    faulted_behavior()
else:
    normal_behavior()
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inject = symbolic_bool()
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```

Definition

A faulted path constraint PC_ω^M is *correct* if every model satisfying PC_ω^M gives entries and faults for a (faulted) execution following the path ω.
A faulted path constraint PC_ω^M is *complete* if every pair (entries, faults) following the path ω is a model satisfying PC_ω^M.
The (faulted) path constraint enumeration PC_ω^M is *correct* if and only if, $\forall PC_\omega^M \in \mathcal{E}^M$, PC_ω^M is *correct*.
The (faulted) path constraint enumeration PC_ω^M is *complete* if and only if:

- $\forall PC_\omega^M \in \mathcal{E}^M$, PC_ω^M is *complete*, **and**,
- for all path $\omega \in \Omega^M$, $\exists PC_\omega^M \in \mathcal{E}^M$ such as PC_ω^M gives entries and faults for a (faulted) execution following the path ω.

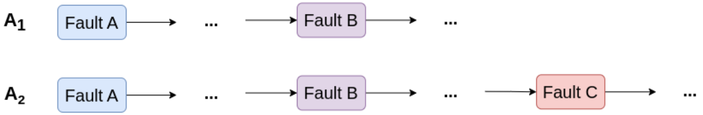
Redundancy / Equivalence

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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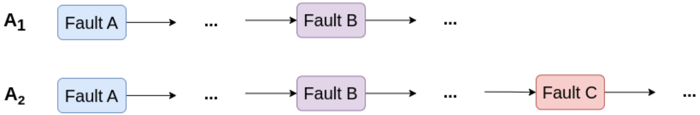
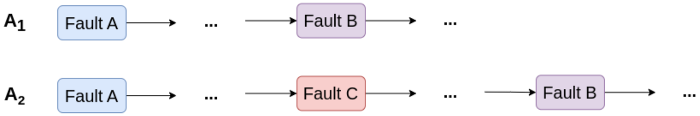


Definition (Redundancy subword)

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



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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)

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

Outline

Lazart overview

Lazart [12] is an LLVM-level multi-fault robustness evaluation tool based on Dynamic-Symbolic Execution (KLEE)

$\rightarrow$ Help developer to develop secure code

$\rightarrow$ Help auditor to find vulnerabilities

$\rightarrow$ Help for evaluation of countermeasures schemes

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- Support for fault models combination
- Fine description of fault space
- Notion of redundancy and equivalence

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Fault models

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

→ cover most of high-level fault models

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
Attacks	0	1	5	10	11

Attack analysis - `verify_pin`

Figure: The 2-faults attack (Test Inversion)

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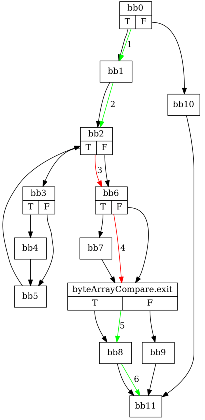
- A successful 2-order attack (right) inverts the loop's condition i < size and the later check if(i != size) killcard();



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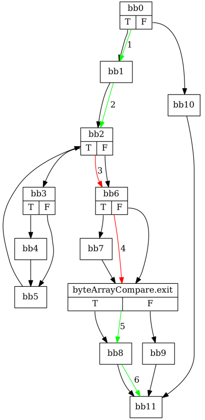
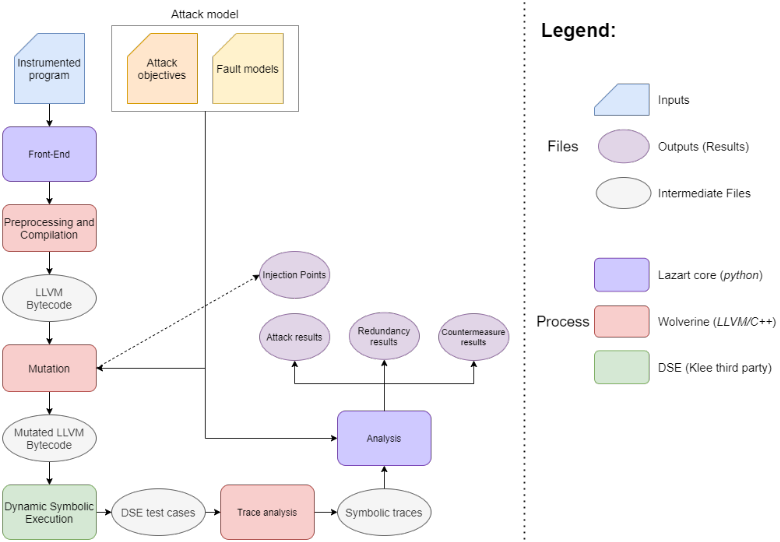
→ How to simplify the attacks presented to the user in multiple faults ?

Figure: The 2-faults attack (Test Inversion)



CFG for 'verifyPIN' function

Lazart: source level analysis for multiple faults injection



Program instrumentation

Symbolic input are used for:

- Symbolic inputs (using `klee_make_symbolic`).
- Attack objective (predicate verified by `_LZ__ORACLE`
- Faults (symbolic boolean determining if the fault is activated).

Fault can be defined:

- Using Python analysis script (see later).
- By program instrumentation (for some fault models).

Listing: Instrumentation example with Lazart

```c
int foo(int a, int b)
{
    if(b == 0)
        return a;
    return a / b;
}

int main() {
    int a;
    int b;
    // (memory pointer, size, name):
    klee_make_symbolic(&a, sizeof(a), "a");
    klee_make_symbolic(&b, sizeof(b), "b");

    int result = foo(a, b);

    _LZ__ORACLE(result > 0); // attack objective
        .
}
```

Analysis script example

```python
#!/usr/bin/python3

from lazart.lazart import *

# Parse CLI parameters
params = install_script()

data_sym = data_model({"vars": { # Explicit value description
    "len": 0, # len is faulted using fixed value.
    "res": "__sym__" # res is faulted using symbolic value.
}})


# Create analysis or load from path if available
a = read_or_make(["src/verify_pin.c", "src/main.c"], # Source files
    functions_list(["verify_pin", "compare"], [ti_model(), data_sym]), # Attack model
    path="results", # Pass in which analysis file will be stored
    flags=AnalysisFlag.AttackAnalysis, # Attack analysis (default)
    compiler_args="-Wall", # Compiler arguments
    params=params, # Pass CLI params to the analysis
    klee_args=""
)

execute(a) # Execute analysis, print results and generate report

verify.attack_analysis(a)
verify.traces_parsing(a)
```

Injecting a fault - mutation function

```
int lz_mutation_data_i32(int original, int fault_limit, int (*predicate)(int),
     const char* ip_name)
{
    int inject, value;
    klee_make_symbolic(&inject, sizeof(inject), "inject");
    if (inject && fault < fault_limit){
        klee_make_symbolic(&value, sizeof(value), "value");
        klee_assume(predicate(value));
        fault++;
        printf("[FAULT] at %s from %d to %d\n", ip_name, original,
             klee_get_value_i32(value));
        return value;
    }
    return original;
}
```

- check that a new fault injection should be done
- in the positive case, the injected value should be used instead of the original one
- possibly, the new injected value should satisfy some constraints
- each injected fault is logged for later processing

LLVM mutation example

- Original bytecode

```
[...]
%6 = load i32* %tmp, align 4
%7 = sext i32 %6 to i64
%8 = call i32 @memcmp(i8* %4, i8* %5, i64 %7) #5
%9 = icmp ne i32 %8, 0
br i1 %9, label %bb26, label %bb25
```

- a fault injection is simulated by a call to the mutation function
- data injection on variable %tmp
- test inversion : injection on first operand of the instruction br

- Mutated bytecode

```
[...]
%6 = alloca i32
%7 = load i32* %tmp, align 4
%funCall4 = call i32 @lz_mutation_data_i32(i32
      %7, i32 4, i32 (i32)* @P_tmp, i8*
      getelementptr inbounds ([9 x i8]* @"bb24:
      tmp", i32 0, i32 0)) #4
store i32 %funCall4, i32* %6, align 4
%8 = load i32* %6, align 4
%9 = sext i32 %8 to i64
%10 = call i32 @memcmp(i8* %4, i8* %5, i64 %9)
      #5
%11 = icmp ne i32 %10, 0
%12 = sext i1 %11 to i32
%funCall5 = call i32 @lz_mutation_test_inversion
      (i32 %12, i32 4, i8* getelementptr
      inbounds ([5 x i8]* @memcmps_s2, i32 0,
      i32 0), i8* getelementptr inbounds ([5 x
      i8]* @memcmps_s3, i32 0, i32 0), i8*
      getelementptr inbounds ([5 x i8]*
      @memcmps_s4, i32 0, i32 0)) #4
%13 = icmp ne i32 %funCall5, 0
br i1 %13, label %bb26, label %bb25
```

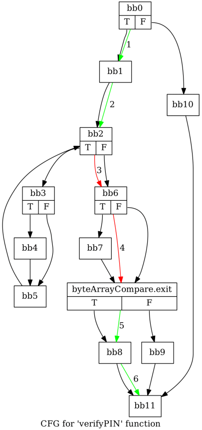
Processing KLEE's results

- LLVM bytecode provided to Klee is instrumented with `printf` to log:
  - basic blocks traversed
  - faults injected
  - others (countermeasures triggered, custom events...)
- traces are obtained from ktests files using Klee's replay tools and parsing stdout logs
- traces are then used in subsequent analysis of Lazart

Figure: VerifyPIN 2-fault attack trace (Python API)

```
>>> t22 = attacks_results(analysis)[22]
>>> print(t22)
(<2> t22: [BB(bb0), BB(bb1), BB(bb2), FAULT(bb2 -> bb6), BB(bb6), FAULT(bb6 -> b
yteArrayCompare.exit), BB(byteArrayCompare.exit), BB(bb8), BB(bb11), ]: Correct)
>>>
```

Figure: VerifyPIN 2-fault attack graph



Lazart's interface

User's input:

- attack objectives are expressed with `klee_assume`
- fault models and fault injection scopes are defined in a strategy file
- finer granularity with source instrumentation

Lazart's other features:

- python API for
  - manipulation of analysis and traces
  - generation of reports and attacks graphs
- automated countermeasure application (test duplication, SecSwift)

```yaml
fault-models:
  - &ti
    type: test-inversion
  - &dl
    type: data
    var:
      - tmp: 0
      - x: symbolic
      - y: symbolic
fault-scope:
  functions:
    - __all__:
      - *ti
    - foo:
      - type: data
        all: symbolic
    - bar:
      - *dl
```

Demo

LIVE DEMONSTRATION

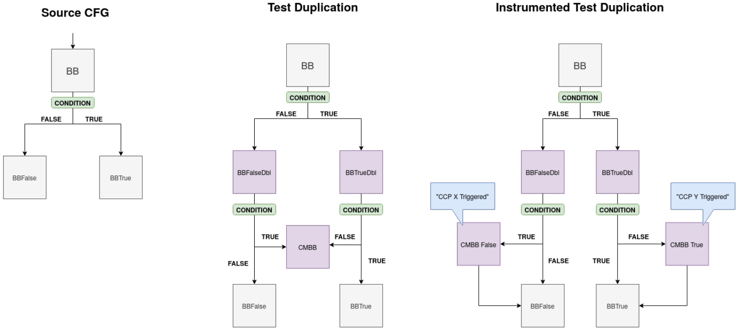
Outline

Countermeasures

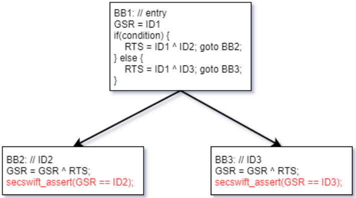
- **Countermeasures** are software modification that doesn't change the software nominal behavior (without fault) but improve software security in case of faults.
- Comparing protected program in multiple fault is not trivial.
- Software countermeasures, three classes:
  - Detective countermeasures: some checks are placed in the program to verify some security properties. Detection is represented in Lazart using `_LZ__CM();` function.
  - Infective countermeasures: in case of fault, the result is made unusable.
  - Others: complete program modifications etc.

Test Duplication

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



SecSwift Control-Flow



SecSwift ControlFlow is one of the 3 parts of SecSwift[16]

- 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 [5]

```c
#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

Conclusion

- Multi fault make difficult to analyze programs (longer analysis times).
- Fault models depends on the representation level (physical, µarchitectural, binary, software, logcal...).
- Lazart uses DSE at LLVM level to produce multiple fault attacks tests cases.

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