Analyzing Software Security against Complex Fault Models with Frama-C Value Analysis

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Summary

I. Introduction

- **There are multiple ways to study the security of software against fault injection.**
- **Software methods are based on software fault models (defined by the Joint Interpretation Library for example [1])**
  - Instruction skip [2]
  - Control-flow corruption (test inversion, …) [3][4]
  - Register/memory corruptions [5][6]
- **The methods are usually closely coupled with a particular fault model**
- **Problem: there are hardware fault effects that are not modelled in typical software fault models [7]**

I. Introduction

- **Some effects obtained in simulation in the LowRISC v0.2 processor [8]:**
  - Replace an argument by the last computed value
  - Make an instruction “transient”
  - Set an architectural register to 0 or 1 during a branching instruction
  - Commit a speculated instruction
  - …
- **Lot of complexity in modelling these models**
- **How to conduct efficient security analyses with these complex software fault models?**

Summary

II. Software fault injection with complex fault models

a. Problem: Complexity of the models

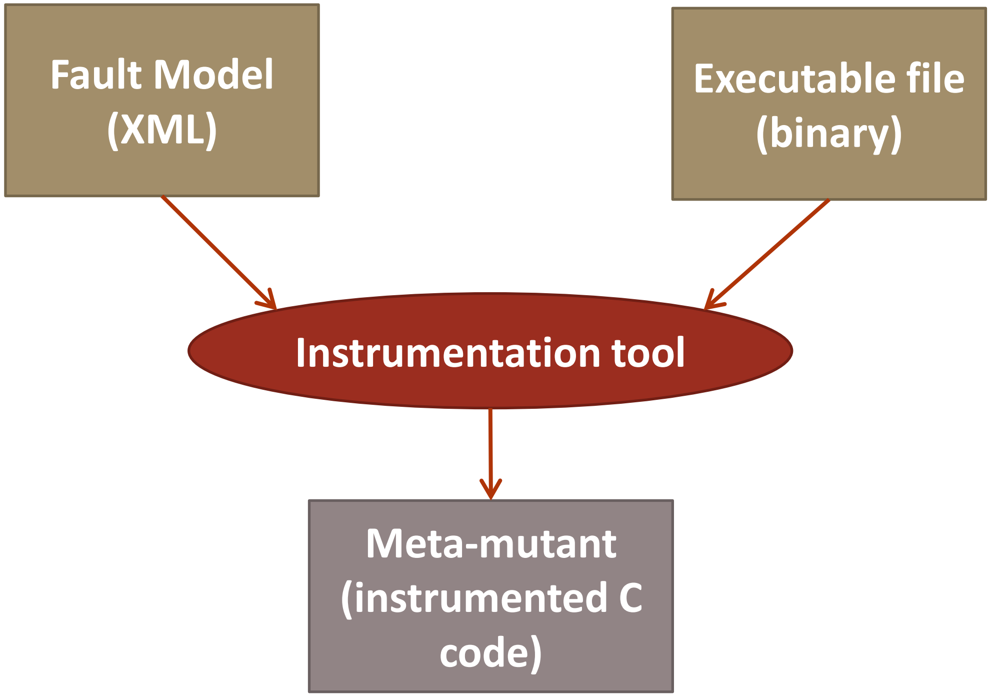
- **How to take these complex software models into account ?**

- **Constraints:**
  - Models very different from one another
  - Need to model certain structures of the processor
  - Need to allow static analyses

II. Software fault injection with complex fault models

b. Solution: Code instrumentation

- **Solution:**
  – From the executable, construct an instrumented C code to inject faults from complex software fault models



II. Software fault injection with complex fault models

b. Solution: Code instrumentation

- **Goal : reproduce at the software level the behavior of the hardware**

```
<model name=”FFM”>
    <globals>      long fwd1 = 0,   fwd2 = 0;      </globals>
    <gold_end>     fwd2 = fwd1;    fwd1 = res;      </gold_end>
    <fault_ini>   if(injection_time==count) arg1=fwd2;  </fault_ini>
</model>
```

```
                [...]
0x06ac:    ADDI  x15 = x0 + 85
                [...]
```

Instrumentation tool

II. Software fault injection with complex fault models

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```

```
[…]
0x06ac:  ADDI  x15 = x0 + 85
[…]
```

Instrumentation tool

1

```
l06ac: // ADDI x15, x0, 85
  arg1 = reg[0];  arg2 = 85;          // Decode
  res = arg1 + arg2;                  // Execute
  reg[15]=res;                        // Write-Back
```

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[…]
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Instrumentation tool

2

```
l06ac: // ADDI x15, x0, 85

 arg1 = reg[0];  arg2 = 85;         // Decode

 res = arg1 + arg2;                 // Execute
 fwd2=fwd1; fwd1=res;
 reg[15]=res;                       // Write-Back
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Instrumentation tool

3

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res = arg1 + arg2;                   // Execute
fwd2=fwd1; fwd1=res;
reg[15]=res;                         // Write-Back
```

II. Software fault injection with complex fault models

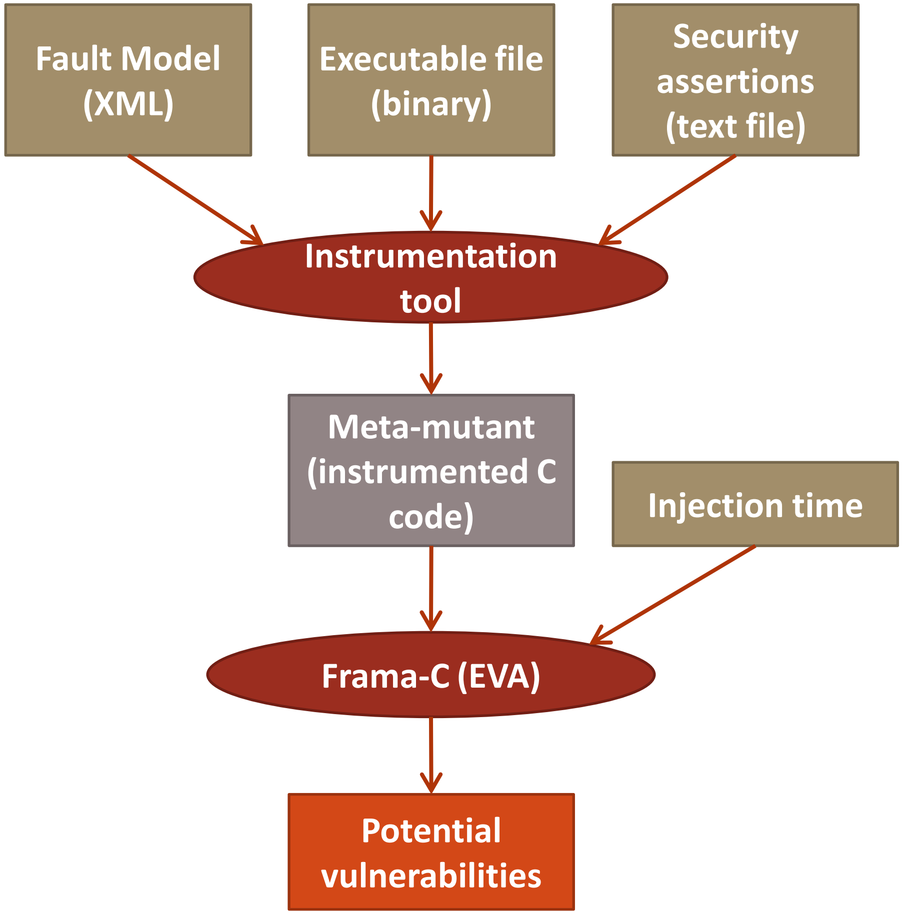
b. Solution: Code instrumentation

- **Verification of the method (fault-free):**
  - Goal: verify that the generated code behaves correctly
  - Use of RISC-V test vectors
  - Test of each instruction with different values and contexts, and comparison with pre-computed values

Summary

III. Security analysis with Frama-C Value Analysis

- **Static analysis is used to prove the validity of security properties (for example, check the number of loop iterations)**



III. Security analysis with Frama-C Value Analysis

- **Value analysis is based on *abstract interpretation***
- **Abstract interpretation [9] is used to abstract the semantics of an application. Concretely, it computes results on intervals instead of concrete values**
  - Instead of analyzing the program with individual values, we can analyze “simultaneously” many values.

```
int a = {0..9}
a++;                // a = {1..10}
```

- **It computes an over-approximation of the results (*sound* and *incomplete*)**

```
int a = {0..9}
a++;                // a = {1..10}
a = pow(a,2);       // a = {1..100}
```

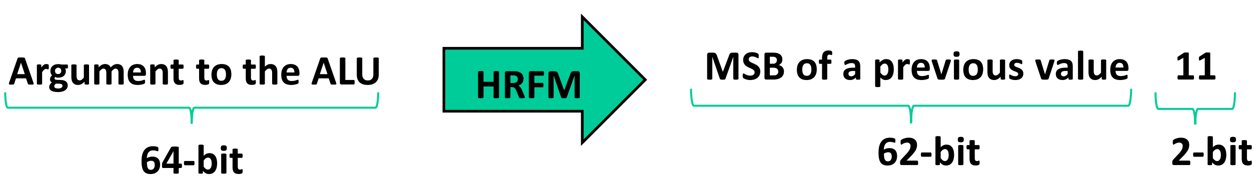
Summary

IV. Case study: VerifyPIN

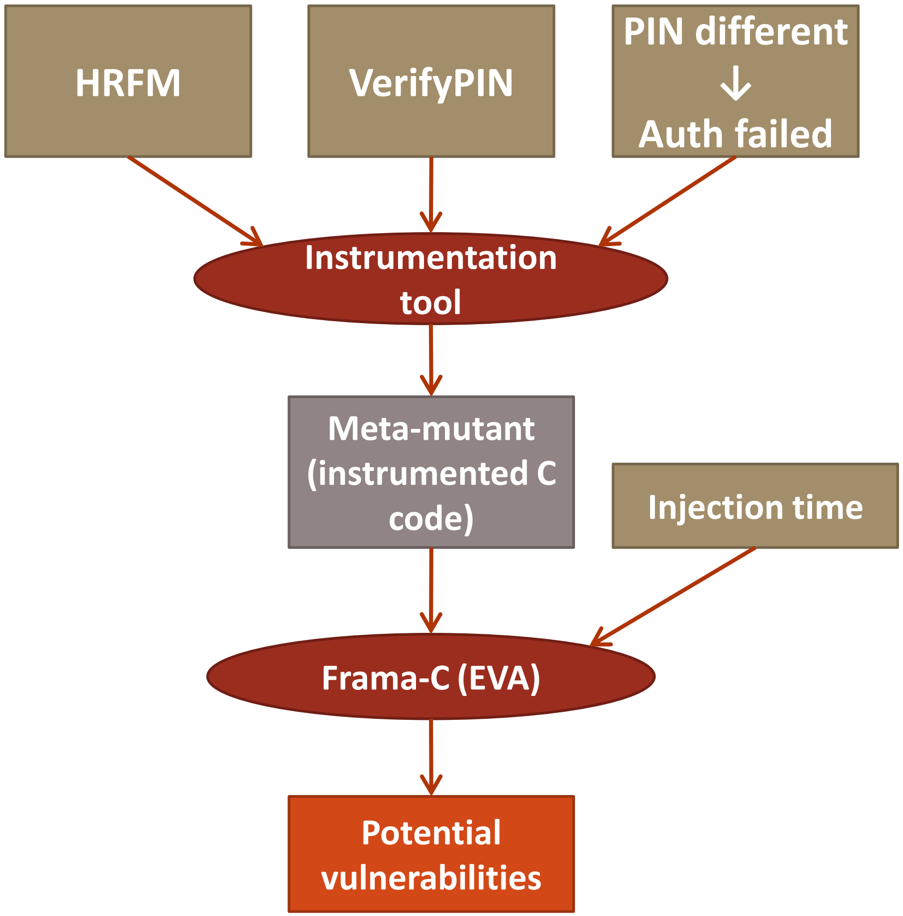
- **VerifyPIN is a protected 4-digit PIN verification from the FISSC library [10], with the following countermeasures:**
  - Hardened Booleans (0x55 for false and 0xAA for true)
  - Verification of the loop counter at the end of the loop
  - Duplicated Boolean tests.

- **Security property: If secret and user PIN are different, do not authenticate (the secret digits and user digits are abstracted (detailed later))**

- **Software Fault model HRFM (Hidden Register Fault Model): model obtained through RTL simulation**



IV. Case study: VerifyPIN



IV. Case study: VerifyPIN

- **There are 50 injection times possible:**
  - For 45, the property is *proven* secure against all user inputs
  - The other 5 (which point to the same instruction) are *potentially* vulnerabilities

- **A manual analysis showed that: if the first digit of the secret PIN has a value 0, 1, 2 or 3, the fault can reduce the program to two loop iterations instead of four**
  - → The countermeasures are not effective in this case (in particular the one that checks the loop counter)
  - → 40% of the possible secret PIN are vulnerable

- **How easy would it be to find the vulnerability with classical tools (with concrete values) ?**
  - The attack is successful if the first secret digit is 0-3 (40%) AND two loop iterations succeed (1%) ➔ overall, only 0.4% to find the vulnerability with concrete values

IV. Case study: VerifyPIN

- **The attack was simulated at RTL**
- **It shows that:**
  - Complex fault models lead to undetected successful attacks
    - ➔ Justifies the use of the instrumentation tool
  - Some attacks only happen under specific circumstances, difficult to find using random, concrete data
    - ➔ Justifies the use of static analysis

Summary

V. Discussion

a. Invariant properties

- **How did we abstract the values in the case study ?**
  - First idea: set all digits to {0..9} (secret: XXXX ; user: XXXX)
    with the property : “if the PIN are different, do not authenticate”
  - Problem: Value analysis does not keep track of *relations* between variables
  - Solution: manually set a secret digit to a concrete value, and the corresponding user digit to everything except that value
    (secret: 0XXX ; user: ≠XXX)
    with the property: “do not authenticate”
- **The properties have to be *invariant* regarding the abstracted states**
  - In the example, we know that for all the abstracted states, the authentication has to fail
  - If we wanted to check the number of loop iterations, we could use secret:XXXX and user:XXXX, since the loop count should always be 4

V. Discussion

b. Performances

- **How efficient is the method to analyze a program, compared to testing every value individually ?**
  - With the property: authentication ? 2.5x
  - With the property: loop count ? 10x
  - With 7-digit PIN instead of 4-digit: 2.5Mx and 10Mx

- **Performances are difficult to estimate**
  - Depends on multiple factors: abstraction, property used, fault model, application, semantic unrolling, etc
  - Experiments on AES AddRoundKey: 2^{256} states at once; analysis can take minutes or hours depending on the settings

V. Discussion

c. False positives

- **False alarms mean that the property is not correct, but do not mean that there is a vulnerability**
- **Value analysis computes an over-approximation of the states → false alarms**
  - No counter-examples
  - Need further analysis (with other tools or manually)
- **The primary goal of the method is to prove the correctness of security properties, not to find vulnerabilities**
  - In the AES experiments, on the 190 possible injection times, 141 were proven safe and 49 undecidable

VI. Conclusion

- Our tool can generate a C code that embeds complex software fault models
- Frama-C Value analysis can then be used to verify security properties whatever the user inputs.
- Although its performances are good compared to a simple execution with concrete values, it can be difficult to define correct properties
- The analysis either proves a property (is correct), or does not (but that does not mean that there is a vulnerability). The remaining cases have to be studied more closely.

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Thanks for your attention !

Questions ?

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