Verifying Redundant-Check Based Countermeasures: A Case Study

MFS 2022, Fréjus, March 21-23, 2022

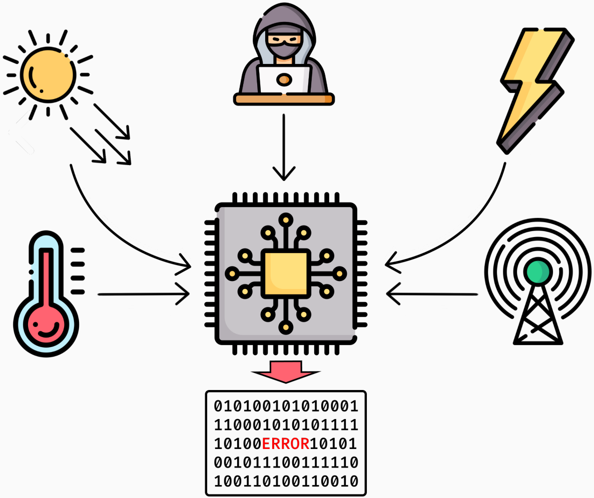
Thibault Martin[1], Nikolai Kosmatov[1,2], Virgile Prevosto[1]

[1]Université Paris-Saclay, CEA, List, Palaiseau, France
firstname.lastname@cea.fr
[2]Thales Research & Technology, Palaiseau, France
nikolaikosmatov@gmail.com

Outline

Fault Injection and Countermeasures

Fault Injection



Test Inversion and Redundant-check Based Countermeasures

Fault model: test inversion, a very useful model [ANSSI & Inter-ITSEF, SSTIC'20]

- Attacker can invert up to k arbitrary tests (checks) in the code (for a given $k \geq 0$)
- It is unlikely to inject $k+1$ faults in a coordinated way

Countermeasure: redundancy of checks for critical conditions

- repeat (possibly, rewritten) critical checks at least $k+1$ times each

Example: for $k = 1$, a password check is repeated twice

- If attackers bypass one check, the redundant check still prevents access.

```
if(password != secret) return 1;
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// Protected area
```

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Motivation: Verification of Countermeasures

How to ensure that countermeasures are correctly implemented?

Verification Approach

Find patterns and delimit critical code

The user needs to delimit the critical section(s) and to identify the protected point(s)

```
// Critical zone start
if(C_1) return 1; // Error
...
if(C_N) return 1; // Error
// Protected area

// Critical zone end
```

Instrumentation to Simulate Faults

```
// Critical zone start
if(C_1)
  return 1;
...

if(C_N)
  return 1;
// Protected area
// Critical zone end
```

→

```
int mut_1 = mutated();
if((!mut_1 && C_1) || (mut_1 && !C_1))
  return 1;
...
int mut_N = mutated();
if((!mut_N && C_N) || (mut_N && !C_N))
  return 1;
/*@ check !mut_1 && ... && !mut_N;*/
//Protected area
```

Instrumentation to Simulate Faults

- `mut_i` represents a mutation trigger for C_i
- `mutated()` returns `true` at most k times non-deterministically
- The assertion states that the protected area can never be entered after a mutation (i.e. an attack)

```
int mut_1 = mutated();
if((!mut_1 && C_1) || (mut_1 && !C_1))
  return 1;
...
int mut_N = mutated();
if((!mut_N && C_N) || (mut_N && !C_N))
  return 1;
/*@ check !mut_1 && ... && !mut_N;*/
//Protected
```

Prove Assertions Using Automatic Tools

- Apply deductive verification
- Try to prove the check annotation

```
int mut_1 = mutated();
if((!mut_1 && C1) || (mut_1 && !C1))
  return 1;
...
int mut_N = mutated();
if((!mut_N && CN) || (mut_N && !CN))
  return 1;
/*@ check !mut_1 && ... && !mut_N;*/
//Protected
```

If the check annotation is proved, the specified critical section is correctly protected

Modeling Mutation Triggers: mutated() returns true at most k times

```
unsigned int cpt_mut = 0;
/*@
  assigns cpt_mut;
  behavior cannot_mutate:
    assumes cpt_mut ≥ k;
    ensures !\result;
    ensures cpt_mut == \at(cpt_mut, Pre);
  behavior can_mutate:
    assumes cpt_mut < k;
    ensures  \result ⟺ cpt_mut == \at(cpt_mut,Pre) + 1;
    ensures !\result ⟺ cpt_mut == \at(cpt_mut,Pre);
*/
int mutated();
```

Difficulties: Function calls and loops

Deductive Verification without Annotations?

Weakest precondition is in general well-adapted for local reasoning but can face issues:

Function calls

- How to avoid the need to write function contracts?

➤ Inline called functions

➤ It can make proof complex

➤ It can introduce loops

Loops

- How to avoid writing loop contracts?

➤ Use loop unrolling

➤ It can duplicate critical areas

➤ Loop bounds can be high / unknown

Focus: Critical Area vs. Loop Conditions ?

```
// Critical area starts here ?
int i = 0;
while(i < SIZE){
    // or starts here ?
    if(password[i] != secret[i]) return 1;
    if(password[i] != secret[i]) return 1;
    ...
    i++;
    // Critical area ends here ?
}
// or ends here ?
```

Vulnerability of Non-protected Loop Conditions

```
// Critical area start
int i = 0;
while(1){
  // Injection here can lead to undefined behavior
  if(!(i < SIZE)) break;
  if(password[i] != secret[i]) return 1;
  if(password[i] != secret[i]) return 1;
  ...
  i++;
}
// Critical area end
```

Solution: Protect Loop Conditions by Redundancy

```
// Critical area start
int i = 0;
while(i < SIZE){
    if(!(i < SIZE)) break;
    if(password[i] != secret[i]) return 1;
    if(password[i] != secret[i]) return 1;
    ...
    i++;
}
// Critical area end
```

Duplication Patterns

- Redundant-check countermeasures can follow different kinds of patterns
- We need to know which pattern is used to perform a correct instrumentation

```
if(password != secret) return 1;
if(password != secret) return 1;
```

```
if(password != secret || password != secret) return 1;
```

Implementation

Implemented in Frama-C and LTest

- Frama-C: a platform for C program verification developed by CEA List
- Frama-C/Wp: weakest precondition based tool for deductive verification
- Frama-C/LTest: toolset for program testing
  - LAnnotate: performs code instrumentation
  - LUncov: Calls Wp to attempt a proof of assertions
- If all assertions are proved, specified critical sections are correctly protected

WooKey Case Study

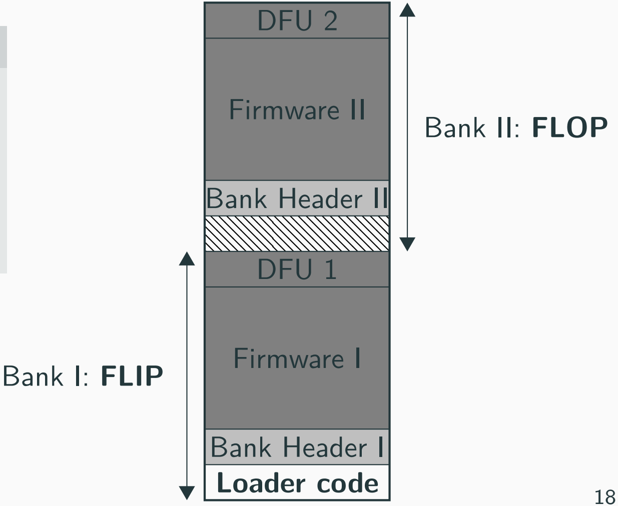
WooKey: A secure USB Mass Storage

- Open-source and open-hardware
- Developed by the ANSSI
- Secured by data encryption

Architecture

Bootloader

- Select boot mode
- Select one of two boot areas
- CRC and Integrity check
- Boot



Example of Countermeasure in WooKey

Several countermeasures with code redundancies

```
/* Double sanity check (for faults) */
if(fw->fw_sig.len > partition_size){
    goto err;
}
if(fw->fw_sig.len > partition_size){
    goto err;
}
```

Results of Experiments

- 11 critical sections using countermeasures
- 3 involving loops and function calls
- 9 proved correct
- 1 cannot be proved without annotations (probably correct)
- 1 incorrect countermeasure found (and proved after fixing)

Incorrect Countermeasure: No Protection

```
/* Duplicated check */
if (new_state == 0xff && !(new_state != 0xff)) {
  dbg_log("%s: PANIC! this should never arise!",__func__);
  dbg_flush();
  loader_set_state(LOADER_ERROR);
  return;
}
//Safe code
```

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Correct Implementation: Protection is Ensured

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}
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```

Good Patterns

Pay attention to what you are trying to protect:

```
/* Double if protection */
if (C1 && C1) {
  // Safe code
}
// Error
```

```
/* Double if protection */
if (C1 || C1) {
  // Error
}
// Safe code
```

Conclusion and Future Work

Conclusion and Future Work

Summary

- A new method to prove correctness of redundant-check countermeasures
- Implemented in Frama-C and LTest
- Successfully applied to a real case study: WooKey
  - Automatically proved 90% of countermeasures
  - Helped to find an incorrect one

For more detail, see [Martin et al, SAC-SVT'22]

What's next?

- Other experiments and case studies
- Combine with tools for attack generation