Verifying the Use of Unsigned Integers in Linux Device Driver Code

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Verification of Linux Device Drivers

Software in safety/mission critical systems must be correct!

Problems with FLOSS:

- Many different (external) programmers
- No single source that guarantees quality

Opportunity with FLOSS:

- Open Source permits Open Correctness checks
  - by user/reseller of the FLOSS
  - by verification provider
  - by the community

Why device drivers?

- Device drivers are part of the operating system
- Device drivers have error rates up to three to seven times higher than the rest of the kernel

Infiniband Device Driver

Goal: Verification of the Infiniband/EHCA Device Driver
(in loose cooperation with IBM Böblingen Labs.):

Infiniband is

- a switched fabric communications link
- used in high performance computing

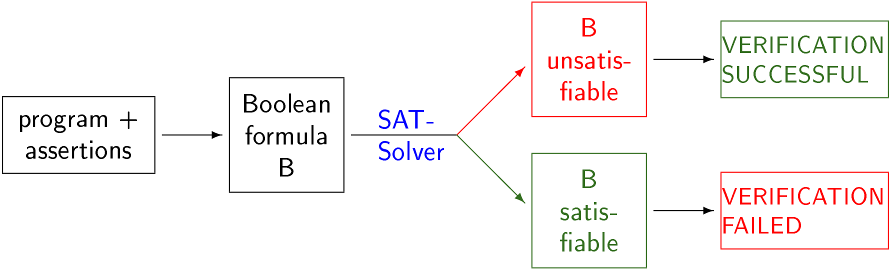
EHCA is

- an IBM specific implementation of the Infiniband standard
- used on IBM's Z series („Zero downtime") mainframes

$\rightarrow$ EHCA driver is critical for performance and reliability

Verification by Bounded Model Checking (BMC)

1. Manually add assertion(s) to program: **assert(property)**
2. Automatically prove/disprove the assertion by BMC
   - CBMC compiles program + (negated) assertion to a Boolean formula and solves it with a SAT-Solver without human help



Research Problems

Some problems

- What is the power of Bounded Model Checking and CBMC?
- „Assertion Engineering:“ How to write the assertions?
- How to add global assertions to the program in all the right places?
- How to precondition the program?
    - Remove constructs not accepted by CBMC
    - Abstract from CBMC
- How to catch compiler errors?

In general, a tool-chain is needed (cf. Avinux [PostSinzKuechlin 2008])

- Write assertions
- Weave assertions into the program
- Precondition the program
- Call the verifier back-end

CBMC: C Bounded Model Checker

CBMC: verification tool for C programs by Clarke, Kroening and Lerda
Bounded: Cut loops to bounded length

Example (Prove/Disprove using CBMC)

```
int main() {
    int x = 3;
    int y = 4;
    assert(x * y == 12);
}
```

CBMC-output:

```
VERIFICATION SUCCESSFUL
```

```
int main() {
    int x = 3;
    int y = 5;
    assert(x * y == 12);
}
```

CBMC-output:

```
Violated property:
line 4 function main
assertion
   x * y == 12
VERIFICATION FAILED
```

CBMC Advanced Example 1

Function: `a << 4`. Property: `(a << 4) == a*16`.

```
unsigned int multiply16(unsigned int a) {
        unsigned int p = a << 4;
        assert(p == a * 16);
        return p;
}
```

command line output:

```
cbmc mult.c --function multiply16
file mult.c: Parsing
Converting
...
Solving with MiniSAT2 without simplifier
78 variables, 107 clauses
SAT checker: negated claim is UNSATISFIABLE, i.e., holds
Runtime decision procedure: 0.001s
VERIFICATION SUCCESSFUL
```

CBMC Advanced Example 2

Function: `abs(x)`. Property: `abs(x) >= 0`.

```
short myabs(short a) {
  short result;
  if (a < 0)
    result = -a;
  else
    result = a;
  assert(result >= 0);
  return result;
}
```

CBMC output:

```
  abs::myabs::1::result=-32768 (1000000000000000)

Violated property:
  file test.c line 8 function myabs
  assertion
  result >= 0

VERIFICATION FAILED
```

Integer data types in C

signed	**unsigned**
(signed) char	unsigned char
(signed) short	unsigned short
(signed) int	unsigned int
(signed) long	unsigned long
(signed) long long	unsigned long long
s8	u8
s16	u16
s32	u32
s64	u64

Problem

- Unsigned integers represent non-negative values only.
- If negative integer values are assigned, the program continues.
- The bit-pattern is re-interpreted as a positive integer.

Example of Undetected Misuse

Example

```
s32 some_function() {
        return -5;
}

int main() {
        u32 u;
        s32 s = -13;

        u = s;
        u = some_function();
        u = -1;
}
```

The code compiles and runs without error!

More Examples

The misuse may work just fine *sometimes* . . .

<table>
<tr>
<td><pre>u32 u = -1;
if (u == -1)
  printf("yes");
else
  printf("no");</pre></td>
<td><pre>u8 u = -1;
if (u == -1)
  printf("yes");
else
  printf("no");</pre></td>
<td><pre>u32 u = -1;
if (u < 0)
  printf("yes");
else
  printf("no");</pre></td>
</tr>
<tr>
<td>Output: yes</td>
<td>Output: no</td>
<td>Output: no</td>
</tr>
</table>

A Possible Explanation

- ```
  u32 u = -1;
  if (u == -1) ...
  ```

Bit pattern u (32 bits)	1111 1111 1111 1111 1111 1111 1111 1111
Bit pattern -1 (32 bits)	1111 1111 1111 1111 1111 1111 1111 1111

  ⇒ Bit patterns are equal, `(u == -1)` yields *true*.

- ```
  u8 u = -1;
  if (u == -1) ...
  ```

Bit pattern u (8 bits)	1111 1111
Bit pattern u (32 bits)	0000 0000 0000 0000 0000 0000 1111 1111
Bit pattern -1 (32 bits)	1111 1111 1111 1111 1111 1111 1111 1111

  ⇒ u is extended to 32 bits.

  ⇒ Since u is unsigned extension is by zeroes.

  ⇒ Bit patterns are different, `(u == -1)` yields *false*.

Error Patterns Checked

- Assigning constant to Unsigned Integer

Example

```
u = 4;
u = -3;
```

- Comparing constant to Unsigned Integer

Example

```
u == -3;
u < 0;
u == 4;
```

- Assigning variable value to Unsigned Integer

Example

```
u = s;
u = some_function();
```

How to write the assertions

Problem situation

```
u = <exp>;
```

1st Ansatz

```
assert(<exp> >= 0); u = <exp>;
```

→ Wrong! `<exp>` may have side-effects!

2nd Ansatz

```
u = t = <exp>; assert(t >= 0);
```

→ Better, but no universal type for `t`.

3rd Ansatz

```
typeof(<exp>) t; u = t = <exp>; assert(t >= 0);
```

→ More complicated, but universal solution.

Weaving Assertions into the Program Automatically

- CBMC can add assertions for some types of problems automatically:
  - Array Bounds
  - Division by Zero
  - Arithmetic Overflow
- How can we add an assertion for every assignment to an unsigned type?
  $\Rightarrow$ need a tool which weaves **our** assertions into the source code.
- Similar to Aspect Oriented Programming
  $\Rightarrow$ weave statements for „verification aspect“ into source code.

Annotator: Source Code Annotation

Our (Flex/Bison-based) tool for source-code annotation with Unsigned-Assertions.

- Catches easy errors by itself
  - `unsigned = negative_constant`
  - `unsigned == negative_constant`
  - and similar ...
- Annotates hard case `unsigned = variable_value` with assertion.

↓

(Unsigned-)Annotator

Handles easy cases by itself, annotates hard cases

↓

CBMC

Proves / disproves assertions for hard cases.

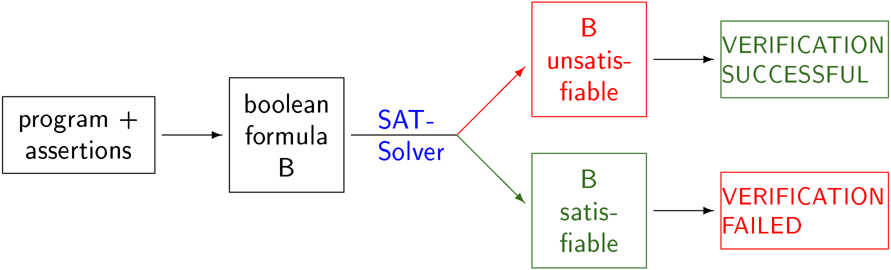
Example Annotation

```
u16 a;
....
a = f(x) + c;
...
```

$$\Downarrow$$

```
u16 a;
....
typeof(f(x) + c) t; a = t = f(x) + c; assert(t >= 0);
...
```

Reminder: Verification with CBMC



Why Preconditioning?

Preconditioning: prepare the annotated code for processing by CBMC

- At the time, CBMC could not handle Gnu-C (only ANSI C)
- At the time, CBMC could not handle embedded Assembler
- Now Gnu-C is accepted, as well as embedded Assembler

General reasons for preconditioning:

- Abstract from verifier back-end
  - Remove statements or modify assertions which back-end cannot process
- Catch compiler errors/optimizations
  - Pass code through compiler front-end first
  - Generate fresh C code from compiler intermediate code
- Abstract from source language
  - Many compilers can emit C code
  - Different back-ends may accept different language flavors

A Toolchain for Pre-Processing LINUX code

↓

remove-asm.pl

removes embedded assembler statements

↓

llvm-gcc -c -emit-llvm

Translates C-Code into LLVM-Bytecode

↓

llc -march=c

Translates LLVM-Bytecode back to (ANSI) C-Code

↓

CBMC

Proves or disproves assertions

Uses of Unsigned Ints in the Infiniband Driver

1. Using Annotator:
    - Annotator catches 16 easy errors by itself
    - Weaves assertions into the source-code
2. Applying CBMC:
    - Device drivers don't have a `main` function
    - CBMC must be called repeatedly on all 47 EHCA entry functions
        - 3 × CBMC aborts due to internal error
        - 5 × verification takes more than 3 hours
        - 31 × CBMC proves all assertions
        - 8 × CBMC disproves one or more assertions
    - CBMC catches a total of 11 errors.
    - CBMC takes about 10sec on most entry functions
    - CBMC takes more than 20sec on 7 out of 44 entry functions

(Easy) Errors Found by Annotator

File	Line	Error type
include/linux/mm.h	1279	unsigned = negative number
ehca_irq.c	145	unsigned = negative number
hcp_if.c	783	unsigned = negative number
ehca_cq.c	235	unsigned < 0
ehca_cq.c	358	unsigned == negative number
ehca_irq.c	155	unsigned == negative number
hcp_if.c	251	unsigned == negative number
hcp_if.c	289	unsigned == negative number
hcp_if.c	364	unsigned == negative number
hcp_if.c	559	unsigned == negative number
hcp_if.c	595	unsigned == negative number
hcp_if.c	603	unsigned == negative number
hcp_if.c	638	unsigned == negative number
hcp_if.c	660	unsigned == negative number
hcp_if.c	699	unsigned == negative number
ehca_irq.c	721	unsigned == negative number

(Hard) Errors found by CBMC

File	Line
hcp_if.c	386, 534, 557, 594, 601, 697, 866
ehca_uverbs.c	272, 294
ehca_mrmw.c	808

Summary / Lessons

Summary

- Found 27 bugs in real Linux code in real industrial setting
- 11 bugs found by formal verification tool
- Built source-code annotation tool
  - specialized for Unsigned errors
  - generalizable approach

Lessons

- Formal software verification is here
- Tools like CBMC find real errors in real code at compile-time
- General specification language is needed
- Tool-chain is needed
  - Pre-process „foreign" languages (Gnu-C, C++, . . .)
  - Abstract from verifyer back-end (CBMC, . . .)
  - Weave global assertions/specifications into programs

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Thank you for your attention!

Questions ?