

Work Package 4: "Validation & Verification Strategy"

Final Report on Validation and Verification Report of Implementation/Code

Jens Gerlach and Izaskun de la Torre

March 2015



Funded by:


 Federal Ministry
of Education
and Research

 Région de
Bruxelles-
Capitale

 GOBIERNO
DE ESPAÑA
MINISTERIO
DE INDUSTRIA, ENERGÍA
Y TURISMO

This page is intentionally left blank

Work Package 4: “Validation & Verification Strategy”**OETCS/WP4/D4.3.2
March 2015**

Final Report on Validation and Verification Report of Implementation/Code

Document approbation

Lead author:	Technical assessor:	Quality assessor:	Project lead:
location / date	location / date	location / date	location / date
signature	signature	signature	signature
Jens Gerlach (Fraunhofer FOKUS)	Virgile Prevosto (CEA LIST)	Abdelnasir Mohamed (AEbt)	Klaus-Rüdiger Hase (DB Netz)

Jens Gerlach

Fraunhofer FOKUS
 Kaiserin-Augusta-Allee 31
 10589 Berlin, Germany
jens.gerlach@fokus.fraunhofer.de
www.fokus.fraunhofer.de

Izaskun de la Torre

Software Quality Systems S.A.

Intermediate report

Prepared for openETCS@ITEA2 Project

Abstract: This work package will comprise the activities concerned with verification and validation within openETCS. This includes verification & validation of development artifacts, that is, showing that models and code produced correctly express or implement what they are supposed to. And also, methods and tools to perform such tasks will be evaluated with the goal of assembling a suitable method and tool chain to support a full development.

Disclaimer: This work is licensed under the "openETCS Open License Terms" (oOLT) dual Licensing: European Union Public Licence (EURL v.1.1+) AND Creative Commons Attribution-ShareAlike 3.0 – (cc by-sa 3.0)

THE WORK IS PROVIDED UNDER openETCS OPEN LICENSE TERMS (oOLT) WHICH IS A DUAL LICENSE AGREEMENT INCLUDING THE TERMS OF THE EUROPEAN UNION PUBLIC LICENSE (VERSION 1.1 OR ANY LATER VERSION) AND THE TERMS OF THE CREATIVE COMMONS PUBLIC LICENSE ("CCPL"). THE WORK IS PROTECTED BY COPYRIGHT AND/OR OTHER APPLICABLE LAW. ANY USE OF THE WORK OTHER THAN AS AUTHORIZED UNDER THIS OLT LICENSE OR COPYRIGHT LAW IS PROHIBITED.

BY EXERCISING ANY RIGHTS TO THE WORK PROVIDED HERE, YOU ACCEPT AND AGREE TO BE BOUND BY THE TERMS OF THIS LICENSE. TO THE EXTENT THIS LICENSE MAY BE CONSIDERED TO BE A CONTRACT, THE LICENSOR GRANTS YOU THE RIGHTS CONTAINED HERE IN CONSIDERATION OF YOUR ACCEPTANCE OF SUCH TERMS AND CONDITIONS.

<http://creativecommons.org/licenses/by-sa/3.0/>
<http://joinup.ec.europa.eu/software/page/eupl/licence-eupl>

Table of Contents

Figures and Tables	iv
List of code examples	v
List of Corrections	vi
1 Introduction	1
1.1 Software layers	3
1.2 Structure of this document	4
2 An introduction to formal verification with Frama-C/WP	7
2.1 First steps	8
2.2 Why can Frama-C/WP not verify such a simple function?	8
2.3 Sharpening the contract of <code>abs_int</code>	9
2.4 Separating specification and implementation	11
2.5 Modular verification	11
2.6 Dealing with side effects	13
3 ETCS data packets	17
3.1 Formal specification of <code>AdhesionFactor</code>	17
3.1.1 <code>AdhesionFactor</code> in ETCS	17
3.1.2 The type <code>AdhesionFactor</code>	17
3.1.3 ACSL predicates <code>AdhesionFactor</code>	17
3.1.4 Formal specification of <code>AdhesionFactor_UpperBitsNotSet</code>	19
3.1.5 Formal specification of <code>AdhesionFactor_DecodeBit</code>	19
3.1.6 Formal specification of <code>AdhesionFactor_EncodeBit</code>	21
3.1.7 Formal verification of <code>AdhesionFactor</code>	22
3.2 Formal specification of other packets	22
4 The Bit Stream Layer	23
4.1 The <code>Bitstream</code> abstraction	23
4.2 Reading and writing bit sequences	27
5 Formal verification	31
6 Static analysis	33
7 Conclusion	35
Appendix A: Low-level bitstream operations	37
A.1 Reading and writing individual bits	37
A.1.1 8 bit arrays	37
A.1.2 8 bits.....	38
A.1.3 64 bits	39
A.2 Formalization of bit operations in Frama-C	40
Appendix: References	43

Figures and Tables

Figures

Figure 1.1. Scope of formal methods with in OpenETCS	1
Figure 1.2. Scope of code verification	2
Figure 1.3. Software layers of the OpenETCS C code	3
Figure 4.1. Bit coincidences required by <code>EqualBits</code>	24
Figure A1. Bit coordinates in Frama-C and in the OpenETCS project	41

Tables

Table 2.1. Test results for <code>abs_int</code>	9
Table 3.1. Packet <code>AdhesionFactor</code> as defined by ETCS	17

List of code examples

2.1	An implementation of the absolute value function	8
2.2	A first attempt to formally specify <code>abs_int</code>	8
2.3	Some simple test cases for <code>abs_int</code>	9
2.4	Taking integer overflows into account	10
2.5	Minimal contract to ensure the absence of runtime errors in <code>abs_int</code>	11
2.6	Specifying a function prototype in a header file	11
2.7	Implementation at a different location than the specification	11
2.8	A simple example of modular verification	12
2.9	Another example of modular verification.....	12
2.10	A more complex example of modular verification	13
2.11	An implementation with side effects.....	13
2.12	Calling a logging function from <code>abs_int</code>	14
2.13	Specifying the absence of side effects	15
2.14	Finer control of side effects	15
3.1	Definition of the type <code>AdhesionFactor</code>	17
3.2	Definition of the <code>BitSize</code> predicates for <code>AdhesionFactor</code>	18
3.3	Definition of the <code>Invariant</code> predicate for <code>AdhesionFactor</code>	18
3.4	Definition of the <code>UpperBitsNotSet</code> predicate for <code>AdhesionFactor</code>	18
3.5	Definition of the <code>Separated</code> predicate for <code>AdhesionFactor</code>	19
3.6	Definition of the <code>EqualBits</code> predicate for <code>AdhesionFactor</code>	19
3.7	Contract for <code>UpperBitsNotSet</code> function of <code>AdhesionFactor</code>	19
3.8	Contract for <code>DecodeBit</code> function of <code>AdhesionFactor</code>	21
3.9	Contract for <code>EncodeBit</code> function of <code>AdhesionFactor</code>	22
4.1	Reading from a bitstream.....	24
4.2	Details for the bitstream data structure.....	24
4.3	ACSL predicates used in bitstream layer contracts.....	25
4.4	Setting-up a bitstream	25
4.5	Testing a bitstream for exhaustion.....	26
4.6	Writing to a bitstream	26
4.7	Reading a bit sequence.....	27
4.8	ACSL predicates used in bitsequence layer contracts	28
4.9	Writing a bit sequence.....	29
A.1	Reading a bit of an <code>uint8_t</code> array.....	37
A.2	Writing a bit of an <code>uint8_t</code> array	38
A.3	Reading a bit of <code>uint8_t</code>	39
A.4	Writing a bit of <code>uint8_t</code>	39
A.5	Reading a bit of <code>uint64_t</code>	40
A.6	Writing a bit of <code>uint64_t</code>	40
A.7	Test that upper bits are not set.....	40
A.8	Definition of bit test predicates.....	41
A.9	Definition of the low-level predicate <code>UpperBitsNotSet</code>	41
A.10	The Frama-C library predicate <code>BitTest</code>	42

List of Corrections

Fatal: fix linebreak in itemize	20
Fatal: unrealistic!?	24
Fatal: ja, wofuer denn eigentlich?	40
Fatal: Is there any documentation available? What about negative numbers?	41

1 Introduction

In this intermediate report we describe the activities to formally verify the correctness of parts of the software developed in the OpenETCS project.

While major parts of the functionality of Subset 026 are modelled in higher-level languages, there is also a substantial part of *supporting* software that is developed in the C programming language.

In this document we report about results on the verification of that C code. In particular, we report on the use of static analysis methods (including formal methods) on C code that has been developed by the project partner Siemens.

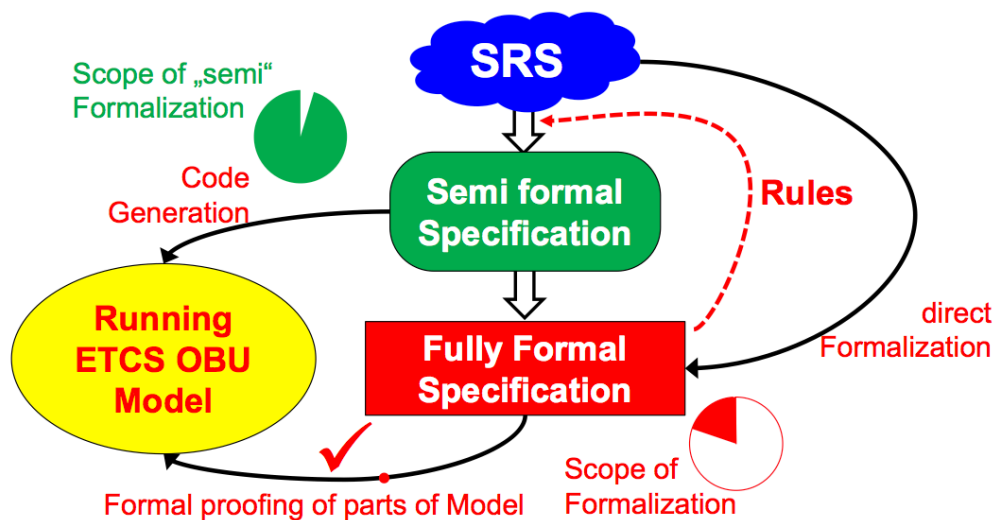


Figure 1.1. Scope of formal methods with in OpenETCS

Figure 1.1 outlines the roles of formal methods within the OpenETCS project. What this figure shall convey is that even a subsystem such as described by *Subset 026* of the ETCS specification is usually too complex to be completely formally specified. Therefore, *semi-formal modelling techniques* and *tests* and *simulations* play a crucial role to verify that the implementation satisfies its specification. However, for clearly defined modules and select system properties, formal methods can well be applied to establish the correctness of an implementation.

Figure 1.2 shows slightly more detailed the OpenETCS software. The report at hand is limited to the parts encapsulated by C software encapsulated in a dashed box.

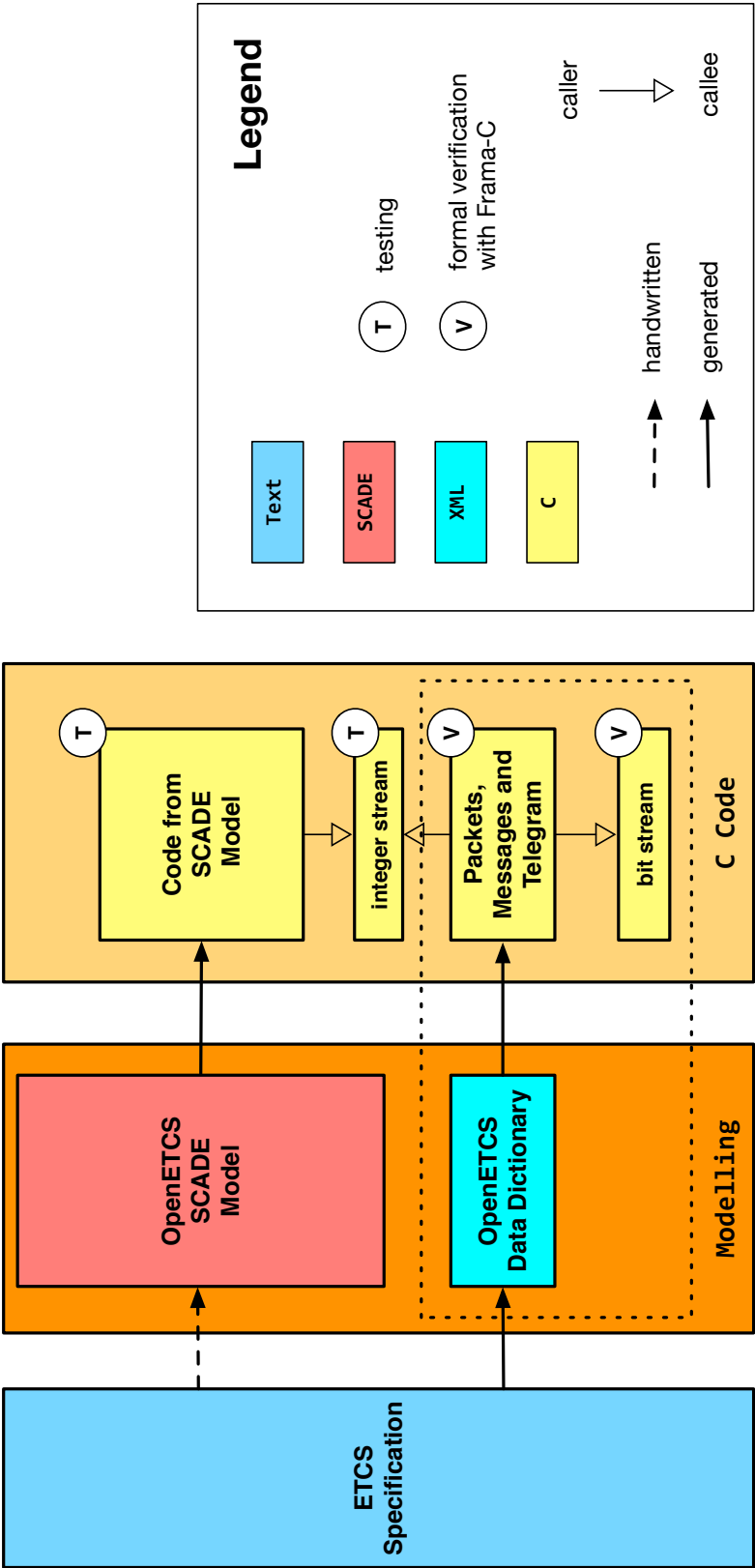


Figure 1.2. Scope of code verification

1.1 Software layers

Figure 1.3 shows the layer structure of the OpenETCS C code.

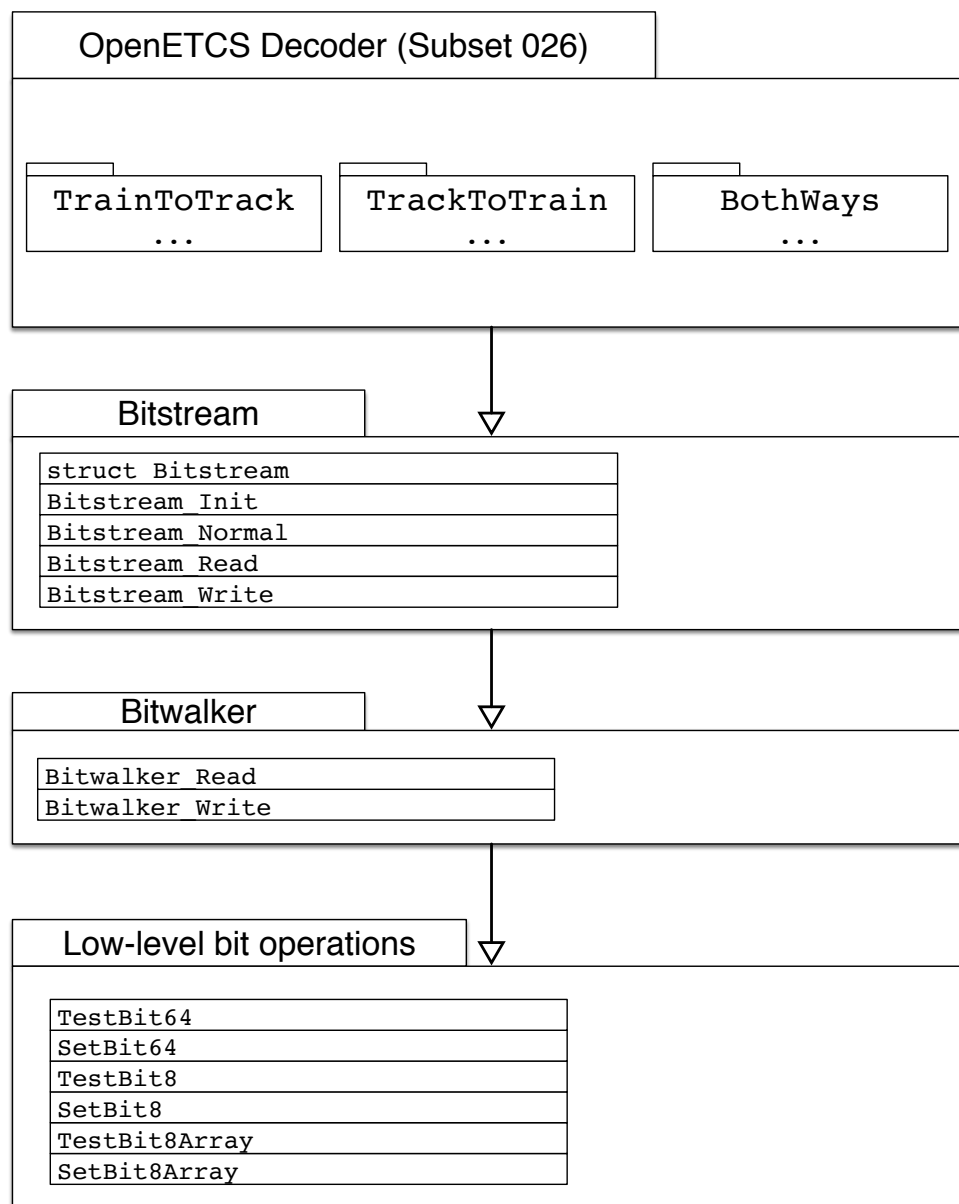


Figure 1.3. Software layers of the OpenETCS C code

The OpenETCS decoder is a large collection of functions dedicated to the reading of ETCS messages. In order to fulfill their task these functions rely on the relatively small software package `Bitwalker`. The `Bitwalker` software, as seen by the OpenETCS decoder, is best understood as a “class” with a handful of methods. Note that this class is implemented in C as a `struct` where the methods are implemented as functions. The core functionality of this class, which consists in converting bit sequences to integers and vice versa, depends on two more basic functions, namely `Bitwalker_Peek` and `Bitwalker_Poke`.

This software has been analyzed by the OpenETCS project partners SQS (Spain) and Fraunhofer FOKUS (Germany). SQS used several static analysis tools to identify defects and to derive useful metrics. Fraunhofer FOKUS, on the other hand, used the Frama-C tool set, which is developed by the French project partner CEA LIST, in order to *formally verify* various properties of the `Bitwalker`.

These analyses contribute to the ultimate verification goals, which are the following:

1. provide evidence that the `Bitwalker` software satisfies accepted quality standards
2. develop a formal specification for the `Bitwalker` software
3. verify that the `Bitwalker` software satisfies its formal specification
4. show that the `Bitwalker` software does not raise runtime errors
5. verify that OpenETCS decoder calls the `Bitwalker` software only according to its specification

We are confident that all these verification goals can be reached. For this preliminary verification report, we provide partial answers to the first four topics. In order to achieve the last goal, more development and verification work is currently conducted by Fraunhofer ESK and Fraunhofer FOKUS.

1.2 Structure of this document

Chapter 2 gives a short overview on the Frama-C/WP tool that plays a central role in the verification of the `Bitwalker` functions. Here we also try to rectify some misunderstandings about formal verification that we have encountered in our work.

In Chapter 5 we analyze the functions `Bitwalker_Peek` and `Bitwalker_Poke` from the `Bitwalker` core and

1. formally specify the expected functional behavior in the ACSL specification language of Frama-C and
2. report on the formal proof that these C functions do not raise runtime errors when called according to their formal specification, established using the Frama-C verification platform.

So far only a part of Siemens' `Bitwalker` has been formalized and verified. In the process of this work several enhancements for the Frama-C verification platform have been identified and reported to the developers at CEA LIST.

In Chapter 6, we report about the results of SQS' application of a broad range of static analysis tools on the `Bitwalker`. In contrast to `Frama-C`, these tools cannot exhaustively detect all potential defects of a given kind. Nevertheless, these they are very useful at finding well-known quality deficiencies that might occur in C or C++ software.

In Chapter 7, we draw conclusions from this preliminary work and outline the next steps in our verification efforts.

2 An introduction to formal verification with Frama-C/WP

Frama-C is a platform dedicated to source-code analysis of C software. It has a plug-in architecture and can thus be easily extended to different kinds of analyses. The WP plugin of Frama-C allows one to formally verify that a piece of C code satisfies its specification. This implies, of course, that the user provides a *formal specification* of what the implementation is supposed to do. Frama-C comes with its own specification language ACSL which stands for *ANSI/ISO C Specification Language*. In order to help potential users to master ACSL we discuss in this chapter a very simple C function `abs_int` that implements the computation of the absolute value for objects of type `int`.

- In Section 2.1 we will present a straightforward specification of `abs_int`. We discuss the reasons why Frama-C/WP is not able to verify that our implementation satisfies this specification in Section 2.2.
- In Section 2.3 we provide a more precise specification that can be verified by Frama-C/WP. In Section 2.4 we explain how Frama-C supports—by allowing the separation of the specification from the implementation—good software engineering practices.
- Sections 2.5 and 2.6 discuss, respectively, how Frama-C/WP supports *modular verification* and the formal treatment of *side effects*.

2.1 First steps

We will consider the function that computes the absolute value $|x|$ of an integer x . In order to avoid name clashes with the function `abs` in C standard library we use the name `abs_int`.

The mathematical definition of absolute value is very simple

$$|x| = \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{if } x < 0 \end{cases} \quad (1)$$

A straightforward implementation of `abs_int` is shown in Listing 2.1.

```
int abs_int(int x)
{
    return (x >= 0) ? x : -x;
}
```

Listing 2.1. An implementation of the absolute value function

In order to demonstrate that this implementation is correct we have to provide a formal specification. Listing 2.2 shows our first attempt for an ACSL specification of `abs_int` that is based on the mathematical definition of the function $x \mapsto |x|$ in Equation 1.

```
/*@
    ensures 0 <= x ==> \result == x;
    ensures 0 > x ==> \result == -x;
*/
int abs_int(int x)
{
    return (x >= 0) ? x : -x;
}
```

Listing 2.2. A first attempt to formally specify `abs_int`

The first thing to note is that ACSL specifications—or *contracts*—are placed in special C comments (they start with `/*@`). Thus, they do not interfere with the executable code. The **ensures** clause in the specification expresses *postconditions*, that is, properties that should be guaranteed *after* the execution of `abs_int`. The ACSL reserved word `\result` is used to refer to the return value of a C function. Note that we use the usual C operators `==` and `<=` to express equalities and inequalities in the specification. There is also an additional operator `==>` which expresses logical implication.

2.2 Why can Frama-C/WP not verify such a simple function?

Although the specification and implementation in Listing 2.2 look perfectly right, Frama-C/WP cannot verify that the implementation actually satisfies its specification.

The reason becomes clear if we look at some actual return values of `abs_int`. Listing 2.3 shows our test code whose output is listed in Table 2.1.


```

#include <stdio.h>
#include <limits.h>

extern int abs_int(int);

void print_abs(int x)
{
    printf("%12d\t\t%12d\n", x, abs_int(x));
}

int main()
{
    printf("\n");
    print_abs(0);

    printf("\n");
    print_abs(1);
    print_abs(10);
    print_abs(INT_MAX);

    printf("\n");
    print_abs(-1);
    print_abs(-10);
    print_abs(INT_MIN);
}

```

Listing 2.3. Some simple test cases for `abs_int`

x	abs_int(x)	Remark
0	0	✓
1	1	✓
10	10	✓
2147483647	2147483647	✓
-1	1	✓
-10	10	✓
-2147483648	-2147483648	✗

Table 2.1. Test results for `abs_int`

The offending value is in the last line of Table 2.1 which basically states that `abs_int(INT_MIN)` equals `INT_MIN` whereas it should equal `-INT_MIN`. The problem is that the type `int` only present a finite subset of the (mathematical) integers. Many computers use a two's-complement representation of integers which covers the range $[-2^{31} \dots 2^{31} - 1]$ on a 32-bit machine. On such a machine `-INT_MIN` cannot be represented by a value of the type `int`.

In a specification, Frama-C/WP interprets integers as mathematical entities. Consequently, there is no such thing as an *arithmetic overflow* when adding or multiplying them. In other words, Frama-C/WP is perfectly right not being able to verify that `abs_int` satisfies the contract in Listing 2.2. Indeed, the implementation does not respect the given specification.

2.3 Sharpening the contract of `abs_int`

It is of course well known that the operation `-x` can overflow and it is the fact that Frama-C/WP can detect such overflows that helps to prevent incorrect verification results.

The GNU Standard C Library clearly states that the absolute value of `INT_MIN` is undefined.¹ Under OSX, the manual page of `abs` mentions under the field of “Bugs”:

The absolute value of the most negative integer remains negative.

Thus, our formal specification should exclude the value `INT_MIN` from the set of admissible value to which `abs_int` can be applied. In ACSL, we can use the **requires** clause to express *preconditions* of a function. Listing 2.4 shows an extended contract of `abs_int` that takes the limitations of the type `int` into account.

```
#include <limits.h>

/*@
  requires x > INT_MIN;

  ensures 0 <= x ==> \result == x;
  ensures 0 > x ==> \result == -x;
*/
int abs_int(int x)
{
  return (x >= 0) ? x : -x;
}
```

Listing 2.4. Taking integer overflows into account

Frama-C/WP is now capable to verify that the implementation of `abs_int` satisfies the specification of Listing 2.4.

There is an important lesson that can be learned here:

Sometimes developers provide source code and imagine that a tool like Frama-C/WP can verify the correctness of their implementation. In order to fulfill its task, however, Frama-C/WP needs an ACSL specification. Such a specification—which must be based on a reasonably precise description of the admissible inputs and expected behavior—has to come from the *requirements* of the software and is not magically discovered from the source code by Frama-C/WP. The code does what it does. In order to verify that the code does what someone expects, these expectations must be clearly expressed, that is, they must be formally specified.

Of course, it might not always be the goal to verify the complete functionality of a piece of software. Sometimes, it is enough to ensure that individual software components cause no runtime errors, that is, arithmetic overflows or invalid pointer accesses. Frama-C/WP can also be used in this situation. Under the terms of the following minimal specification in Listing 2.5, Frama-C/WP can verify that no runtime error will occur.

¹See http://www.gnu.org/software/libc/manual/html_node/Absolute-Value.html

```

#include <limits.h>

/*@
    requires x != INT_MIN;
*/
int abs_int(int x)
{
    return (x >= 0) ? x : -x;
}

```

Listing 2.5. Minimal contract to ensure the absence of runtime errors in `abs_int`

2.4 Separating specification and implementation

Before we continue exploring more advanced specification and verification capabilities of Frama-C/WP we turn to a simple software engineering question.

It is common practice to put function prototypes into “.h” files and keep the implementation in files ending in “.c”. Frama-C/WP supports this separation of specification and implementation. Listing 2.6 shows the file `abs2.h` which contains a declaration of `abs_int` together with an attached ACSL specification.

```

#include <limits.h>

/*@
    requires x > INT_MIN;

    ensures 0 <= x ==> \result == x;
    ensures 0 > x ==> \result == -x;
*/
int abs_int(int x);

```

Listing 2.6. Specifying a function prototype in a header file

Listing 2.7 shows the specification of `abs_int` in a .c file. Note that the file `abs2.h` with the specification is included by this file. Frama-C/WP can verify that this implementation satisfies the contract in Listing 2.6.

```

#include "abs2.h"

int abs_int(int x)
{
    return (x >= 0) ? x : -x;
}

```

Listing 2.7. Implementation at a different location than the specification

We remark, that the definition of a very small function like `abs_int` would normally be placed in a header file so that a compiler can inline the function definition at the call site.

2.5 Modular verification

We now look at a simple example in which our function `abs_int` is used. More precisely, we include in Listing 2.8 the header file from Listing 2.6 which contains an ACSL specification of `abs_int`.

```
#include "abs2.h"

void use_1()
{
    int a = abs_int(3);
    int b = abs_int(-1);
    int c = abs_int(INT_MAX);
    int d = abs_int(INT_MIN);

    // ...
}
```

Listing 2.8. A simple example of modular verification

When Frama-C/WP tries to verify the code in Listing 2.8, then it actually tries to establish whether at each program location where it is called the *preconditions* of `abs_int` are satisfied. Based on the specification of `abs_int`, Frama-C/WP can indeed verify that for the first three calls the preconditions are fulfilled. For the last call this verification fails because the value `INT_MIN` is explicitly excluded by the specification in Listing 2.6.

Note that the *implementation* of `abs_int` does not play any role in determining whether it is safe to call the function in a particular context. This is what we call *modular verification*: a function can be verified in isolation whereas code that calls the function only uses the function contract.

This also means that in a situation as in Listing 2.9, where nothing is known about the argument of `abs_int`, Frama-C/WP cannot establish that the precondition of `abs_int` is satisfied or, in other words, that $x > \text{INT_MIN}$ holds.

```
#include "abs2.h"

void use_2(int x)
{
    int a = abs_int(x);

    // ...
}
```

Listing 2.9. Another example of modular verification

If, on the other hand, we have precise information on the arguments at call site, then Frama-C/WP can exploit the specification of `abs_int` in order to derive some interesting properties. As an example, we consider the code fragment in Listing 2.10. Here, Frama-C/WP can verify that the assertion after the call of `abs_int` is correct.

Note that this assertion is a *static* one, that is, it is an ACSL annotation that resides inside a comment and does not affect the execution of the code in Listing 2.10. Also note that unlike to C code, *relation chains* can be used both in function contracts and assertions.

```

#include "abs2.h"

/*@
    requires (10 <= x < 100) || (-200 < x < -50);
*/
void use_3(int x)
{
    int a = abs_int(x);
    //@ assert 10 <= a < 200;

    // ...
}

```

Listing 2.10. A more complex example of modular verification

2.6 Dealing with side effects

Listing 2.11 shows an implementation of `abs_int` that writes as a side effect the argument `x` to a global variable `a`. A natural question is to ask whether this implementation with a side effect also satisfies the specification.

```

#include <limits.h>

extern int a;

/*@
    requires x > INT_MIN;

    ensures 0 <= x ==> \result == x;
    ensures 0 > x ==> \result == -x;
*/
int abs_int(int x)
{
    a = x; // Is this side effect covered by the specification?
    return (x >= 0) ? x : -x;
}

```

Listing 2.11. An implementation with side effects

Before we answer this question we consider various uses for side effects. There are of course legitimate uses for side effects. The assignment to a memory location outside the scope of the function might be meaningful because an error condition is reported or because some data are logged as in Listing 2.12.

If Frama-C/WP attempts to verify the code in Listing 2.12, then it issues the following warning:

```

Neither code nor specification for function logging,
generating default assigns from the prototype

```

Thus, it points out that the called function `logging` should have a proper specification that clearly indicates its side effects.

There are, on the other hand, also good reasons to minimize or even forbid side effects:

```

#include <limits.h>

extern void logging(int);

/*@
    requires x > INT_MIN;

    ensures 0 <= x ==> \result == x;
    ensures 0 > x ==> \result == -x;
*/
int abs_int(int x)
{
    logging(x);
    return (x >= 0) ? x : -x;
}

```

Listing 2.12. Calling a logging function from `abs_int`

- Imagine a malicious password checking function that writes the password to a global variable.
- Another reason is that side effects can make it harder to understand what the real consequences of a function call are. In particular, one must be concerned about unintended consequences that are caused by side effects. The norm IEC 61508 therefore requests in the context of software module testing and integration testing:

To show that all software modules, elements and subsystems interact correctly to perform their intended function and do not perform unintended functions (see also. [1, §7.4.7.2, §7.7.2.9])

Of course, it is quite difficult to ensure by testing alone that something does *not* happen.

To come back to our question about Listing 2.11 it is important to understand that Frama-C/WP verifies that the implementation shown there satisfies the specification.

If one wishes to forbid that a function changes global variables one can use an `assigns \nothing` clause as shown in Listing 2.13. Frama-C/WP will then point out that this implementation prevents the verification of the assigns clause.

```

#include <limits.h>

extern int a;

/*@
  requires x > INT_MIN;

  assigns \nothing; // forbid any side effects

  ensures 0 <= x ==> \result == x;
  ensures 0 > x ==> \result == -x;
*/
int abs_int(int x)
{
  a = x; // now illegal
  return (x >= 0) ? x : -x;
}

```

Listing 2.13. Specifying the absence of side effects

Of course, an all-or-nothing-approach to side effects is not very helpful for the verification of real-life software. Listing 2.14 shows how the **assigns** clause of a specification can name the exact memory location that the function is allowed to modify.

```

// Side effects can be controlled on an individual basis.

#include <limits.h>

extern int a;

/*@
  requires x > INT_MIN;

  assigns a; // allow assignment to a (but only to a).

  ensures 0 <= x ==> \result == x;
  ensures 0 > x ==> \result == -x;
*/
int abs_int(int x)
{
  a = x;
  return (x >= 0) ? x : -x;
}

```

Listing 2.14. Finer control of side effects

Note however that **assigns a** does not imply that a write to `a` necessarily occurs during the execution of `abs`. On the other hand, any other memory location must stay unchanged between the initial state and the final state of `abs`.

3 ETCS data packets

3.1 Formal specification of `AdhesionFactor`

3.1.1 `AdhesionFactor` in ETCS

Subset 026 defines package *adhesion factor* (packet 71) as shown in Table 3.1.

variable name	number of bits
NID_PACKET	8
Q_DIR	2
L_PACKET	13
Q_SCALE	2
D_ADHESION	15
L_ADHESION	15
M_ADHESION	1

Table 3.1. Packet `AdhesionFactor` as defined by ETCS

3.1.2 The type `AdhesionFactor`

Listing 3.1 shows the definition of type `AdhesionFactor` as it is generated from the ETCS specification shown in Section 3.1.1.

```

struct AdhesionFactor
{
    PacketHeader header;

    // TransmissionMedia=Any
    // This packet is used when the trackside requests a change of
    // the adhesion factor to be used in the brake model.
    // Packet Number = 71

    uint64_t Q_DIR;           // # 2
    uint64_t L_PACKET;       // # 13
    uint64_t Q_SCALE;        // # 2
    uint64_t D_ADHESION;     // # 15
    uint64_t L_ADHESION;     // # 15
    uint64_t M_ADHESION;     // # 1
};

typedef struct AdhesionFactor AdhesionFactor;

```

Listing 3.1. Definition of the type `AdhesionFactor`

3.1.3 ACSL predicates `AdhesionFactor`

Listing 3.2 shows the definition of the logic functions `BitSize` and `MaxBitSize` for `AdhesionFactor`. The former function uses a macro that contains the size of `AdhesionFactor` in bits. The functions

are used in Listing 3.8 and Listing 3.9 where the overloading of the logic predicates allows for a more generic ACSL contract for the `EncodeBit` and `DecodeBit` functions.

```
/*@
  logic integer BitSize{L} (AdhesionFactor* p) = ADHESIONFACTOR_BITSIZE;

  logic integer MaxBitSize{L} (AdhesionFactor* p) = BitSize(p);
*/
```

Listing 3.2. Definition of the `BitSize` predicates for `AdhesionFactor`

Listing 3.3 shows the definition of the `Invariant` predicate for `AdhesionFactor`. The predicate is the conjunction of the (trivial) `Invariant (uint64_t)` predicates of all members of an object of type `AdhesionFactor`.

```
/*@
  predicate Invariant (AdhesionFactor* p) =
    Invariant(p->Q_DIR)          &&
    Invariant(p->L_PACKET)       &&
    Invariant(p->Q_SCALE)        &&
    Invariant(p->D_ADHESION)     &&
    Invariant(p->L_ADHESION)     &&
    Invariant(p->M_ADHESION);
*/
```

Listing 3.3. Definition of the `Invariant` predicate for `AdhesionFactor`

Listing 3.4 shows the definition of the `UpperBitsNotSet` predicate for `AdhesionFactor`. The predicate `UpperBitsNotSet (AdhesionFactor*)` evaluates to true if and only if the values of all members of `AdhesionFactor` fit into their assigned numbers of bits. This functionality is ensured by the conjunction of the `UpperBitsNotSet (uint64_t, uint32_t)` predicate, which is explained in Appendix A.2, for all members of `AdhesionFactor`.

```
/*@
  predicate UpperBitsNotSet (AdhesionFactor* p) =
    UpperBitsNotSet(p->Q_DIR,      2) &&
    UpperBitsNotSet(p->L_PACKET,   13) &&
    UpperBitsNotSet(p->Q_SCALE,    2) &&
    UpperBitsNotSet(p->D_ADHESION, 15) &&
    UpperBitsNotSet(p->L_ADHESION, 15) &&
    UpperBitsNotSet(p->M_ADHESION, 1);
*/
```

Listing 3.4. Definition of the `UpperBitsNotSet` predicate for `AdhesionFactor`

Listing 3.5 shows the definition of predicate `Separated` for `AdhesionFactor`. The predicate `Separated(stream, p)` is true if and only if the two objects `*stream` and `*p` do not overlap in memory. Thus, writing into the stream will not change `*p` and vice versa.

```

/*@
  predicate Separated(Bitstream* stream, AdhesionFactor* p) =
    \separated(stream, p) &&
    \separated(stream->addr + (0..stream->size-1), p);
*/

```

Listing 3.5. Definition of the Separated predicate for AdhesionFactor

Listing 3.6 shows the definition of the `EqualBits` predicate for `AdhesionFactor`. Based on the ETCS specification, this predicate describes a relationship between the bits of the individual members of an object of type `AdhesionFactor` and those of a bit stream. This predicate will be used to formally describe the transfer of bits from a bit stream to an object of type `AdhesionFactor` and vice versa. The definition of the predicate `EqualBits (AdhesionFactor*)` uses the predicate `EqualBits (uint64_t)`, which is explained in Section 4.1.

```

/*@
  predicate EqualBits(Bitstream* stream, integer pos, AdhesionFactor* p)
    =
    EqualBits(stream, pos,      pos + 2,  p->Q_DIR)          &&
    EqualBits(stream, pos + 2,  pos + 15, p->L_PACKET)        &&
    EqualBits(stream, pos + 15, pos + 17,  p->Q_SCALE)         &&
    EqualBits(stream, pos + 17, pos + 32,  p->D_ADHESION)       &&
    EqualBits(stream, pos + 32, pos + 47,  p->L_ADHESION)       &&
    EqualBits(stream, pos + 47, pos + 48,  p->M_ADHESION);
*/

```

Listing 3.6. Definition of the EqualBits predicate for AdhesionFactor

3.1.4 Formal specification of AdhesionFactor_UpperBitsNotSet

Listing 3.7 shows the contract of the `UpperBitsNotSet` function for `AdhesionFactor`. The function contract includes the **requires** clauses, labeled `valid` and `invariant`. These limit the significance of the **ensures** and **assigns** clauses to the `AdhesionFactor` objects that also satisfy the **requires** clauses. The `valid` clause only evaluates to true if the `*p` is a valid pointer. The `invariant` clause requires `Invariant (p)` to evaluate to true. The `Invariant (AdhesionFactor*)` predicate is explained in Section 3.1.3. The contract also includes a statement on the return value of the function, labeled `result`. This clause ensures that the function's return value for `AdhesionFactor* p` matches the evaluation of the predicate `UpperBitsNotSet (p)` from Section 3.1.3. With the **assigns** `\nothing` clause the contract furthermore specifies that this function has no side effects.

```

/*@
  requires valid:      \valid_read(p);
  requires invariant:  Invariant(p);

  assigns \nothing;

  ensures result:      \result <==> UpperBitsNotSet(p);
*/
int AdhesionFactor_UpperBitsNotSet(const AdhesionFactor* p);

```

Listing 3.7. Contract for UpperBitsNotSet function of AdhesionFactor

3.1.5 Formal specification of AdhesionFactor_DecodeBit

Listing 3.8 shows the contract for the `DecodeBit` function for `AdhesionFactor`. The behavior of the function is specified using the two disjoint behaviors `normal_case` and `error_case`. The

requirements `valid_stream`, `stream_invariant`, `valid_package` and `separation` apply to both behaviors and limit the set of combinations of input arguments for which the **ensures** and **assigns** clauses describe the behavior of the function.

The **assigns** clauses in the contract's body describe the side effects of the function. If the function contract is split into multiple behaviors, like here, common **assigns** clauses, which contain the union of the behavior's **assigns** clauses, are needed outside of the behaviors. Their meaning will become clear when discussing the individual behaviors.

For both behaviors the `unchanged` clause states that none of the bits in the bit stream are written by the function.

- `valid_stream` is only met if `Readable(stream)` applies. The `Readable(Bitstream*)` predicate is described in Chapter 4.1.
- `stream_invariant` is only met if `*stream` is long enough to read an object of the length of `AdhesionFactor` from. The `Invariant(Bitstream*, integer)` predicate is introduced in Chapter 4.1.
- `valid_package` is only met if `p` is a valid pointer for read and write operations.
- `separation` requires that `*stream` and `*p` do not overlap in the memory. The `Separated(Bitstream*, AdhesionFactor)` predicate is introduced in Section 3.1.3.

FiXme Fatal: fix linebreak in itemize

`normal_case` describes the function's behavior if `*stream` contains enough unread bits to fill all members of `*p`. In this case an object of type `AdhesionFactor` is decoded from the stream and thus `*p` is written. The latter is stated by the first **assigns** clause. In this context the **ensures** clauses `equal` and `upper` describe the relationship of the bits in the bit stream and the bits of the members of `*p`. Furthermore `stream->bitpos` will be updated. The effects of this operation are described by the second **assigns** and the `increment` clauses.

`error_case` describes the function's behavior in the opposite case i.e. if `*stream` is exhausted before all members of `*p` are read. In this case the function has no side effects and especially does not write `*p` or `stream->bitpos`. The **ensures** clause `result` states, that the return value of the function equals 0. In `normal_case` this value is specified to equal 1.

The distinguishing predicate for the two behaviors is `Normal(Bitstream*, integer)`, which appears in the **assumes** clauses within both behaviors and is explained in Chapter 4.1.

```

/*@
  requires valid_stream:      Readable(stream);
  requires stream_invariant: Invariant(stream, MaxBitSize(p));
  requires valid_package:    \valid(p);
  requires separation:       Separated(stream, p);

  assigns stream->bitpos;
  assigns *p;

  ensures unchanged:         Unchanged{Here,Old}(stream, 0, 8*stream->
    size);

  behavior normal_case:
    assumes Normal{Pre}(stream, MaxBitSize(p));

    assigns stream->bitpos;
    assigns *p;

    ensures invariant:      Invariant(p);
    ensures result:         \result == 1;
    ensures increment:      stream->bitpos == \old(stream->bitpos) + BitSize(
      p);
    ensures equal:          EqualBits(stream, \old(stream->bitpos), p);
    ensures upper:          UpperBitsNotSet(p);

  behavior error_case:
    assumes !Normal{Pre}(stream, MaxBitSize(p));

    assigns \nothing;

    ensures result: \result == 0;

  complete behaviors;
  disjoint behaviors;
*/
int AdhesionFactor_EncodeBit(const AdhesionFactor* p, Bitstream* stream);

```

Listing 3.8. Contract for DecodeBit function of AdhesionFactor

3.1.6 Formal specification of AdhesionFactor_EncodeBit

```

/*@
  requires valid_stream:      Writeable(stream);
  requires stream_invariant:  Invariant(stream, MaxBitSize(p));
  requires valid_package:    \valid_read(p);
  requires invariant:        Invariant(p);
  requires separation:        Separated(stream, p);

  assigns stream->bitpos;
  assigns stream->addr[0..(stream->size-1)];

  behavior normal_case:
    assumes Normal{Pre}(stream, MaxBitSize(p)) && UpperBitsNotSet{Pre}(p)
    ;

    assigns stream->bitpos;
    assigns stream->addr[0..(stream->size-1)];

    ensures result:          \result == 1;
    ensures increment:       stream->bitpos == \old(stream->bitpos) + BitSize(
      p);
    ensures left:            Unchanged{Here,Old}(stream, 0, \old(stream->
      bitpos));
    ensures middle:          EqualBits(stream, \old(stream->bitpos), p);
    ensures right:           Unchanged{Here,Old}(stream, stream->bitpos, 8 *
      stream->size);

  behavior values_too_big:
    assumes Normal{Pre}(stream, MaxBitSize(p)) && !UpperBitsNotSet{Pre}(p)
    );

    assigns \nothing;

    ensures result:          \result == -2;

  behavior invalid_bit_sequence:
    assumes !Normal{Pre}(stream, MaxBitSize(p));

    assigns \nothing;

    ensures result:          \result == -1;

  complete behaviors;
  disjoint behaviors;
*/
int AdhesionFactor_DecodeBit(AdhesionFactor* p, Bitstream* stream);

```

Listing 3.9. Contract for EncodeBit function of AdhesionFactor

3.1.7 Formal verification of AdhesionFactor

3.2 Formal specification of other packets

4 The Bit Stream Layer

4.1 The `Bitstream` abstraction

As mentioned in Section 3, the operations on packet data structures were implemented by operations that on a `struct bitstream*` argument. The latter are described in this section.

The operation `Bitstream_Read(stream, length)` reads the next `length` bits from the bitstream `stream`, and returns them as a `uint64_t` value. Its formal ACSL specification is shown in Listing 4.1. It requires `stream`

- to point to a valid memory area (requirement “`valid`”),
- to adhere to its data type invariant (“`invariant`”), and
- not to be exhausted (“`normal`”).

It is allowed to — and usually in fact will — modify the current bit position within `stream`, but it has to leave all other memory unchanged (expressed by the “`assigns`” clause). After completion of the operation,

- the current bit position has been increased accordingly (“`ensures pos`”),
- the return value equals, bit by bit, the stream between the current bit position on entry and that on exit (“`changed`”),
- in particular, all but the `length` least significant bits² of the return value are zero (“`upper`”),
- `stream`’s total size remains unaffected (“`size`”), and
- so do all of its content bits (“`unchanged`”).

The formal definitions of the ACSL predicates used in `Bitstream_Read`’s contract are given in Listing 4.3; they build upon the internal details of the `Bitstream` data structure shown in Listing 4.2.

- Predicate `Readable` requires that a stream’s data area is complete accessible for read.
- Similarly, `Writeable` requires that it is accessible for update.
- Predicate `Invariant` requires that a `struct Bitstream`’s data area doesn’t overlap with the `struct` itself, and that some further, lower-level invariant holds (see Section 4.2 below).

In a similar way, predicates `Normal` and `EqualBits` is reduced to a lower-level predicate of the same name, respectively.³

² Bit positions are counted differently in Frama-C and in the openETCS project, cf. Figure A1 in Appendix A.2. In this report, we preferably used the terms “least” and “most significant bit(s)” to designate a (range of) bit position(s) independent of the coordinate system.

³Frama-C allows for predicate overloading.

```

/*@
  requires valid:      Readable(stream);
  requires invariant:  Invariant(stream, length);
  requires normal:     Normal(stream, length);

  assigns  stream->bitpos;

  ensures  pos:        stream->bitpos == \old(stream->bitpos) + length;
  ensures  changed:    EqualBits(stream, \old(stream->bitpos), stream->
    bitpos, \result);
  ensures  upper:      UpperBitsNotSet(\result, length);
  ensures  size:       stream->size == \old(stream->size);
  ensures  unchanged:  Unchanged{Here,Old}(stream, 0, 8 * stream->size);
*/
uint64_t Bitstream_Read(Bitstream* stream, uint32_t length);

```

Listing 4.1. Reading from a bitstream

— Insert drawing —

Figure 4.1. Bit coincidences required by `EqualBits`

- A clause `Normal(size, bitpos, length)` requires `bitpos` to be such that at least `length` more bits are available beyond it in a stream of byte-size `size`.⁴
- A predicate call `Unchanged{A,B}(stream, first, last)` succeeds if, and only if, all data bits `[first...last]` of `stream` agree in memory state `A` and `B`. For example, it is used with `A` and `B` instantiated to Frama-C’s reserved keyword “Here” and “Old”, denoting the memory state after and before operation completion and entry, respectively; cf. Listing 4.6.
- A clause `EqualBits(addr, first, last, value)` requires bits `[first...last]` in the byte array at `addr` to coincide with the corresponding least significant bits of `value`, cf. Figure 4.1.

```

struct Bitstream
{
  uint8_t*  addr;      // start address of stream data
  uint32_t  size;      // length of stream data in bytes
  uint32_t  bitpos;    // current bit position within stream data
};
typedef struct Bitstream Bitstream;

```

Listing 4.2. Details for the bitstream data structure

As a kind of constructor for `Bitstream`, we provide the operation `Bitstream_Init`, shown with its contract in Listing 4.4. Moreover, we provide a test for exhaustion of a `Bitstream`, shown in Listing 4.5.

⁴ We tacitly assume that each stream has a multiple of 8 bits available. **Fixme Fatal: unrealistic!?**


```

/*@
  predicate
    Readable{L}(Bitstream* stream) = \valid(stream) &&
      \valid_read(stream->addr + (0..stream->size-1));

  predicate
    Writeable{L}(Bitstream* stream) = \valid(stream) &&
      \valid(stream->addr + (0..stream->size-1));

  predicate
    Invariant{L}(Bitstream* stream, integer length) =
      \separated(stream, stream->addr + (0..stream->size-1)) &&
      Invariant(stream->size, stream->bitpos, length);

  predicate
    Normal{L}(Bitstream* stream, integer length) =
      Normal(stream->size, stream->bitpos, length);

  predicate
    Unchanged{A,B}(Bitstream* stream, integer first, integer last) =
      \forall integer i; first <= i < last ==>
        (\at(Bit8Array(stream->addr, i), A) <==>
          \at(Bit8Array(stream->addr, i), B));

  predicate
    EqualBits{A}(Bitstream* stream, integer first, integer last, uint64_t
      value) =
      EqualBits{A}(stream->addr, first, last, value);

*/

```

Listing 4.3. ACSL predicates used in bitstream layer contracts

```

/*@
  requires valid:      Writeable(stream);
  requires bit_size:   8 * size <= UINT32_MAX;
  requires valid_pos:  bitpos <= 8 * size;
  requires separated:  \separated(addr + (0..size-1), stream);

  assigns stream->addr, stream->size, stream->bitpos;

  ensures addr:        stream->addr == addr;
  ensures size:         stream->size == size;
  ensures bitpos:       stream->bitpos == bitpos;
  ensures invariant:    Invariant(stream, 0);

*/
void Bitstream_Init(Bitstream* stream, uint8_t* addr, uint32_t size,
  uint32_t bitpos);

```

Listing 4.4. Setting-up a bitstream

Listing 4.6 shows contract of `Bitstream_Write`, and moreover exemplifies its implementation.

Most parts of the contract are quite similar to that of `Bitstream_Read` in Listing 4.1. Differences are the following:

- We require that the `value` to be written fits into the specified `length`, i.e. its unused most significant bits are zero (requirement “upper”).

```

/*@
  requires valid:      Readable(stream);
  requires invariant: Invariant(stream, length);

  assigns \nothing;

  ensures result:      \result <==> Normal(stream, length);
*/
int Bitstream_Normal(const Bitstream* stream, uint32_t length);

```

Listing 4.5. Testing a bitstream for exhaustion

- The operation is allowed to change the contents of the bitstream (first `assigns` clause) in addition to the streams current bit position (second `assigns` clause), but no other memory locations.
- Since we couldn't specify in the `assigns` clauses which bits exactly are allowed to be modified, we give the details in two `ensures` clauses named "unchanged": All bits before the stream's `bitpos` on operation entry, and after its `bitpos` on exit, must remain unchanged.

The implementation just employs the lower-level operation `Bitwalker_Write` to write the bits, and appropriately updates the `stream`'s `bitpos`. Two assertions were needed to help the provers establishing that `value`'s bits are actually written to `stream`'s data array by `Bitwalker_Write`, and that they aren't destroyed during `bitpos` update.

```

/*@
  requires valid:      Writeable(stream);
  requires invariant: Invariant(stream, length);
  requires normal:     Normal(stream, length);
  requires upper:      UpperBitsNotSet(value, length);

  assigns stream->addr[0..stream->size - 1];
  assigns stream->bitpos;

  ensures pos:         stream->bitpos == \old(stream->bitpos) + length;
  ensures changed:     EqualBits(stream, \old(stream->bitpos), stream->
    bitpos, value);
  ensures unchanged:   Unchanged{Here,Old}(stream, 0, \old(stream->bitpos))
    ;
  ensures unchanged:   Unchanged{Here,Old}(stream, stream->bitpos, 8 *
    stream->size);
  ensures size:        stream->size == \old(stream->size);
*/
void Bitstream_Write(Bitstream* stream, uint32_t length, uint64_t value)
{
  Bitwalker_Write(stream->addr, stream->size, stream->bitpos, length,
    value);
  //@ assert EqualBits(stream, stream->bitpos, stream->bitpos + length,
    value);

  stream->bitpos += length;
  //@ assert EqualBits(stream, \at(stream->bitpos, Pre), stream->bitpos,
    value);
}

```

Listing 4.6. Writing to a bitstream

4.2 Reading and writing bit sequences

In this section, we describe the operations that handle plain bit sequences. They are used to implement the `struct bitstream*` operations for Section 4.1.

The operation `Bitwalker_Read(addr, size, bitpos, length)` reads `length` bits starting at `bitpos` from the array `addr` of byte-size `size`, and returns them as a `uint64_t` value. Its ACSL contract is shown in Listing 4.7. It requires

- all bytes of the `addr` array to be accessible for read (requirement “`valid`”),
- some data type invariants to hold (“`invariant`”), viz.
 - the total number of array bits to fit into a `uint32_t`,
 - the result value to fit into a `uint64_t`,
 - the end bit position — and hence also the start bit position `bitpos` and `length` — to fit into a `uint32_t`,

and

- the bit range `[bitpos...bitpos+length)` to fit into the array at `addr` (“`normal`”).

The operation is not allowed to modify any (non-local) memory (expressed by the “`assigns`” clause). After completion of the operation,

- the return value shall coincide bit by bit with the specified range of the `addr` array (“`ensures equal`”), and
- in particular, all but the least significant `length` bits of the return value shall be zero (“`upper`”).

```

/*@
requires   valid:      Readable(addr, size);
requires invariant:  Invariant(size, bitpos, length);
requires   normal:    Normal(size, bitpos, length);

assigns    \nothing;

ensures    equal:      EqualBits(addr, bitpos, bitpos + length, \result);
ensures    upper:      UpperBitsNotSet(\result, length);
*/
uint64_t Bitwalker_Read(uint8_t* addr, uint32_t size, uint32_t bitpos,
                        uint32_t length);

```

Listing 4.7. Reading a bit sequence

The formal definitions of the used ACSL predicates are given in Listing 4.8. Again, the tacit assumption that the array contains sensible data upto its very last bit is used in predicate `Normal`.

Listing 4.9 shows the contract, and the implementation, of `Bitwalker_Write`. The following peculiarities are observed when the former is compared to `Bitwalker_Read`’s contract:

- We require that the `value` to be written fits into the specified `length`, i.e. all but its `length` least significant bits are zero (requirement “`upper`”).

```

/*@
  predicate Readable{L}(uint8_t* addr, integer size) = \valid_read(addr +
    (0..size-1));

  predicate Writeable{L}(uint8_t* addr, integer size) = \valid(addr + (0..
    size-1));

  predicate Invariant{L}(integer size, integer bitpos, integer length) =
    8 * size <= UINT32_MAX      &&
    length <= 64                &&
    bitpos + length <= UINT32_MAX;

  predicate Normal{L}(integer size, integer bitpos, integer length) =
    bitpos + length <= 8 * size;
*/

```

Listing 4.8. ACSL predicates used in bitsequence layer contracts

- The operation may modify the data array at `addr`, but nothing else.
- Again, we give the details of which data bits exactly are allowed to be changed in two ensures clauses, named “left” and “right”, and requiring all bits before `bitpos` and after `bitpos+length` to remain unchanged, respectively.

In the implementation, which is shown here as an example, we used the straight-forward algorithm that takes a bit from `value` and places it into the `addr` array, bit by bit. In order for the provers to establish that algorithm’s correctness, we had to provide a total of six ACSL clauses about the loop:

- The loop variable, `i`, always ranges in the interval `[bitpos...bitpos+length]` — loop invariant “bound”. Note that the highest value is actually taken, viz. on exit of the loop body in the last iteration, subsequently causing the loop to terminate.
- The bits before `bitpos`, and after `bitpos+length` remain as they were on operation entry — invariant “left” and “right”, respectively.
- In the `i`th iteration, the bits `[bitpos...bitpos+i)` agree with the least significant `i` bits of `value` — invariant “middle”.
- The loop code is allowed to modify the variable `i`, and the whole array at `addr`, but nothing else — loop assigns clause.
- The value of the integer expression `bitpos+length-i` is non-negative throughout the whole loop execution, but is decreased in every iteration — loop variant clause. Therefore, the loop is guaranteed to terminate eventually.

The implementation of the bit sequence operations is based on operations to write and to read a single bit. The details of the latter, as well as of the predicates used in their contracts, are given in Appendix A.

```

/*@
requires valid:      Writeable(addr, size);
requires invariant: Invariant(size, bitpos, length);
requires normal:     Normal(size, bitpos, length);
requires upper:      UpperBitsNotSet(value, length);

assigns addr[0..size-1];

ensures left:        Unchanged{Here,Old}(addr, 0, bitpos);
ensures middle:      EqualBits(addr, bitpos, bitpos + length, value);
ensures right:       Unchanged{Here,Old}(addr, bitpos + length, 8 * size)
;
*/
void Bitwalker_Write(uint8_t* addr, uint32_t size, uint32_t bitpos,
    uint32_t length, uint64_t value);
{
    /*@
    loop invariant bound:    bitpos <= i <= bitpos + length;
    loop invariant left:     Unchanged{Here,Pre}(addr, 0, bitpos);
    loop invariant middle:   EqualBits(addr, bitpos, i, value, length);
    loop invariant right:    Unchanged{Here,Pre}(addr, i, 8 * size);

    loop assigns i, addr[0..size-1];
    loop variant bitpos + length - i;
    */
    for (uint32_t i = bitpos; i < bitpos + length; ++i)
    {
        int flag = TestBit64(value, (64 - length) + (i - bitpos));
        SetBit8Array(addr, size, i, flag);
    }
}

```

Listing 4.9. Writing a bit sequence

5 Formal verification

6 Static analysis

7 Conclusion

Appendix A: Low-level bitstream operations

In this appendix, we describe the implementation of the low-level bitstream operations. They were used to implement the bit sequence abstraction level, cf. Section 4.2. Since a write operation moves bits from a `uint64_t` value into an array of `uint8_t` values, and a read operations moved them the other way round, we need bit operations on both data types. They are given in Subsection A.1.1 (array of `uint8_t`), A.1.2 (single `uint8_t`), and A.1.3 (single `uint64_t`) below.

A.1 Reading and writing individual bits

A.1.1 8 bit arrays

The operation `TestBit8Array(addr, size, pos)` returns the pos^{th} bit within the array at `addr` of byte-size `size`.⁵ Its contract and its implementation is shown in Listing A.1. See Listing A.8 for the definition of the predicate `Bit8Array`. The array bits are counted starting with the most significant one of the first byte, cf. Figure A1 below. `TestBit8(bytevalue, bitadr)` returns the $\text{bitadr}^{\text{th}}$ bit within `bytevalue`, its is discussed in Appendix A.1.2 below.

```
/*@
  requires valid:  \valid_read(addr + (0..size-1));
  requires size:   8 * size <= UINT32_MAX;
  requires pos:    pos < 8 * size;

  assigns \nothing;

  ensures result:  \result != 0 <==> Bit8Array(addr, pos);
*/
static inline int TestBit8Array(uint8_t* addr, uint32_t size, uint32_t pos
)
{
  return TestBit8(addr[pos / 8], pos % 8);
}
```

Listing A.1. Reading a bit of an `uint8_t` array

Similarly, the operation `SetBit8Array(addr, size, pos, flag)` sets the pos^{th} bit within the array at `addr` of byte-size `size` to `flag`. Its contract is shown in Listing A.2. It requires

- the whole array to be accessible for update (requirement “`valid`”),
- each possible bit position in the array to fit into a `uint32_t` (“`size`”), and
- the given `pos` to be a valid bit position in the array (“`pos`”).

The `assigns` clause allows the operation to change the contents of the array, but no other memory locations. On completion, the operation shall guarantee

⁵ This parameter isn’t actually used in the code, but merely in the contract.

- that the value of `flag`⁶ is actually stored at the designated bit position (“ensures middle”), and
- that all other bits remain unchanged (“left”, “right”).

Two fairly sophisticated hints had to be provided as assertions in the body in order for the provers to establish the contract’s post-conditions.

```

/*@
  requires valid:  \valid(addr + (0..size-1));
  requires size:   8 * size <= UINT32_MAX;
  requires pos:    pos < 8 * size;

  assigns addr[0..size-1];

  ensures left:    Unchanged{Here,Old}(addr, 0, pos);
  ensures middle:  Bit8Array(addr, pos) <==> (flag != 0);
  ensures right:   Unchanged{Here,Old}(addr, pos + 1, 8 * size);
*/
static inline void SetBit8Array(uint8_t* addr, uint32_t size, uint32_t pos,
                               int flag)
{
  uint32_t i = pos / 8u;
  uint32_t k = pos % 8u;

  addr[i] = SetBit8(addr[i], k, flag);

  // The following assertion claims that in byte with index "pos/8"
  // the bits with indices different from "k" do not change
  /*@
    assert bits_in_byte:
      \forall integer j; (0 <= j < 8 && j != k) ==>
        (Bit8(addr[pos/8], j) <==> \at(Bit8(addr[pos/8], j), Pre));
  */

  // The following assertion claims that in every byte
  // with an index that is different from "pos/8" no bit is changed.

  /*@
    assert other_bytes:
      \forall integer l, j; (0 <= l < size && l != pos/8 && 0 <= j <
        8) ==>
        (Bit8(addr[l], j) <==> \at(Bit8(addr[l], j), Pre));
  */
}

```

Listing A.2. Writing a bit of an `uint8_t` array

A.1.2 8 bits

The operation `TestBit8(value, pos)` returns the pos^{th} bit of `value`. Its contract is shown in Listing A.3. `pos` must not exceed 7 (requirement “pre”), no memory may be modified (`assigns`), and the result is non-zero if, and only if, the specified bit is set. The shown implementation additionally guarantees that the result is zero or one, which is not specified in the contract since this property isn’t needed. Returning just `flag` rather than `flag!=0u` would satisfy the contract also, and would be slightly faster.

⁶ Any non-zero `flag` value is treated like 1. This is ensured by the contract of the called operation `SetBit8`, cf. Appendixsubsec:low-level 8.

```

/*@
  requires pre:  pos < 8;

  assigns \nothing;

  ensures pos:  \result != 0 <==> Bit8(value, pos);
*/
static inline int TestBit8(uint8_t value, uint32_t pos)
{
  uint8_t mask = ((uint8_t) 1) << (7u - pos);
  uint8_t flag = value & mask;

  return flag != 0;
}

```

Listing A.3. Reading a bit of `uint8_t`

Dual to `TestBit8`, the operation `SetBit8(value, pos, flag)` returns `value`, with the pos^{th} bit set to `flag`. Its contract is shown in Listing A.4. Again, `pos` mustn't exceed 7 (requirement “pre”), no memory may be modified (`assigns` clause), the return value coincides with `value`, except possibly at `pos` (`ensures` “left” and “right”), and `flag` is written to the appropriate bit of `value` (“pos”). The implementation branches on the value of `flag`, and clears or sets the appropriate bit in the usual way. Note that both our contract and our implementation enable us to set a bit by supplying a `flag` value of e.g. 2, whereas the code `mask=flag<<(7-pos); return (value&~mask)|mask;` does not.

```

/*@
  requires pre:  pos < 8;

  assigns \nothing;

  ensures left:  EqualBits8(\result, value, 0,  pos);
  ensures pos:  Bit8(\result, pos) <==> (flag != 0);
  ensures right: EqualBits8(\result, value, pos + 1, 8);
*/
static inline uint8_t SetBit8(uint8_t value, uint32_t pos, int flag)
{
  uint8_t mask = ((uint8_t) 1) << (7u - pos);

  return (flag == 0) ? (value & ~mask) : (value | mask);
}

```

Listing A.4. Writing a bit of `uint8_t`

A.1.3 64 bits

The operations to read and write a bit of a `uint64_t` are closely similar to those working on a `uint8_t`. They are shown in Listing A.5 and A.6 without repeating the comments given in Appendix A.1.2 for the 8 bit version; see in particular Listing A.8 for the employed ACSL predicates.

As a redundant postcondition of the `SetBit64` operation in Listing A.6, “upper” guarantees that the leading zeros in `value` are kept in the result, up to, but excluding position `pos`. It was needed to enable the provers to verify code that uses `SetBit64`.

```

/*@
  requires pre: pos < 64;

  assigns \nothing;

  ensures set_bit: \result != 0 <==> Bit64(value, pos);
*/
int TestBit64(uint64_t value, uint32_t pos)
{
  uint64_t mask = ((uint64_t) 1) << (63u - pos);
  uint64_t flag = value & mask;

  return flag != 0u;
}

```

Listing A.5. Reading a bit of `uint64_t`

```

/*@
  requires pre: pos < 64;

  assigns \nothing;

  ensures left:      EqualBits64(\result, value, 0, pos);
  ensures set_bit:   flag != 0 <==> Bit64(\result, pos);
  ensures right:     EqualBits64(\result, value, pos + 1, 64);
  ensures upper:     \forall integer i; i >= 64 - pos ==>
                    (UpperBitsNotSet(value, i) ==> UpperBitsNotSet(\
                      result, i));
*/
uint64_t SetBit64(uint64_t value, uint32_t pos, int flag)
{
  uint64_t mask = ((uint64_t) 1u) << (63 - pos);

  return (flag == 0) ? (value & ~mask) : (value | mask);
}

```

Listing A.6. Writing a bit of `uint64_t`

The operation `UpperBitsNotSet64(value, length)` succeeds, i.e. returns a non-zero value, if, and only if, all bits of `value` except the least significant `length` ones are zero. It is used for **FiXme Fatal: ja, wofuer denn eigentlich?**

```

/*@
  requires pre: length <= 64;

  assigns \nothing;

  ensures not_set: \result <==> UpperBitsNotSet(value, length);
*/
int UpperBitsNotSet64(uint64_t value, uint32_t length);

```

Listing A.7. Test that upper bits are not set

A.2 Formalization of bit operations in Frama-C

The definition of predicate `Bit8` is shown in Listing A.8. It relies on the Frama-C library predicate `BitTest`, performing a coordinate transformation to fit Frama-C's notion of bit positions with the OpenETCS project's notion, cf. Figure A1.


```

/*@
  predicate Bit8{A}(uint8_t v, integer n) = BitTest(v, 7 - n);

  predicate Bit64{A}(uint64_t v, integer n) = BitTest(v, 63 - n);

  predicate Bit8Array{A}(uint8_t* a, integer n) = Bit8(a[n / 8], n % 8);
*/

```

Listing A.8. Definition of bit test predicates

— Insert drawing —

Figure A1. Bit coordinates in Frama-C and in the OpenETCS project

The predicate `UpperBitsNotSet(value, length)` succeeds if, and only if, all but possibly the least significant `length` bits of `value` are zero. Its definition is shown in Listing A.9.

```

predicate
  UpperBitsNotSet{A}(integer value, integer length) =
    \forall integer i; length <= i ==> !BitTest(value, i);

```

Listing A.9. Definition of the low-level predicate `UpperBitsNotSet`

The predicate `BitTest(v, n)` succeeds if, and only if, the n^{th} bit is set in the binary representation of `v`, i.e. iff the truncating integer division of `v` by 2^n yields an odd number. **Fixme Fatal: Is there any documentation available? What about negative numbers?** This predicate comes with the standard library of the Frama-C system. Its declaration is shown in Listing A.10.

```
/*@  
  predicate BitTest(integer v, integer n);  
*/
```

Listing A.10. The Frama-C library predicate `BitTest`

Appendix: References

- [1] IEC SC 65A. Functional safety of electrical/electronic/programmable electronic safety-related systems, part 3 software requirements. Technical Report IEC 61508, The International Electrotechnical Commission, 2010.
- [2] Kim Völlinger. Einsatz des Beweisassistenten Coq zur deduktiven Programmverifikation. Master's thesis (Diplomarbeit), Humboldt-Universität zu Berlin, August 2013.
- [3] Virgile Prevosto, Jochen Burghardt, Jens Gerlach, Kerstin Hartig, Hans Werner Pohl, and Kim Voellinger. Formal specification and automated verification of railway software with frama-c. In *INDIN*, pages 710–715, 2013.
- [4] C. A. R. Hoare. An axiomatic basis for computer programming. *Communications of the ACM*, 12(10):576–580 and 583, 1969.
- [5] Coq Development Team. *The Coq Proof Assistant Reference Manual*, v8.3 edition, 2011. <http://coq.inria.fr/>.
- [6] ANSI/ISO C Specification Language. <http://frama-c.com/acsl.html>, March 2014.
- [7] Frama-C Software Analyzers. <http://frama-c.com>, March 2014.
- [8] Loïc Correnson, Pascal Cuoq, Florent Kirchner, Virgile Prevosto, Armand Puccetti, Julien Signoles, and Boris Yakobowski. *Frama-C User Manual*. <http://frama-c.com/download/user-manual-Neon-20140301.pdf>.
- [9] Sylvain Conchon, Evelyne Contejean, and Johannes Kanig. Homepage of the Alt-Ergo Theorem Prover. <http://alt-ergo.lri.fr/>, 2013.
- [10] Clark Barrett and Cesare Tinelli. Homepage of CVC4. <http://cvc4.cs.nyu.edu/web>, 2014.
- [11] WP Plug-in. <http://frama-c.com/wp.html>, March 2014.
- [12] ISO. ISO C Standard 1999. Technical report, ISO/IEC JTC 1, 1999. ISO/IEC 9899:1999 draft.
- [13] J.; Oman, P.W.; Hagemeister and D. Ash. A Definition and Taxonomy for Software Maintainability, 1991.
- [14] Bruce Lowther Dan Coleman, Dan Ash and Paul Oman. Using metrics to evaluate software system maintainability. *IEEE Computer*, 27(8):44–49, 1994.