frama C

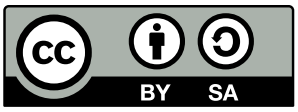
Software Analyzers

Eva – The Evolved Value Analysis plug-in

The Eva plug-in

25.0 (Manganese)

David Bühler, Pascal Cuoq and Boris Yakobowski.
With Matthieu Lemerre, André Maroneze, Valentin Perrelle and Virgile Prevosto



CEA-List, Université Paris-Saclay
Software Safety and Security Lab

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Contents

Chapter 1

Introduction

Frama-C is a modular static analysis framework for the C language.
This manual documents the Eva (for Evolved Value Analysis*) plug-in of Frama-C.*

The Eva plug-in automatically computes sets of possible values for the variables of an analyzed program. Eva warns about possible run-time errors in the analyzed program. Lastly, synthetic information about each analyzed function can be computed automatically from the values provided by Eva: these functionalities (input variables, output variables, and information flow) are also documented here.

The framework, the Eva plug-in and the other plug-ins documented here are all Open Source software. They can be downloaded from http://frama-c.com/.

In technical terms, Eva is context-sensitive and path-sensitive. In non-technical terms, this means that it tries to offer precise results for a large set of C programs. Heterogeneous pointer casts, function pointers, and floating-point computations are handled.

1.1 First contact

Frama-C comes with two interfaces: batch and interactive. The interactive graphical interface of Frama-C displays a normalized version of the analyzed source code. In this interface, the Eva plug-in allows the user to select an expression in the code and observe an over-approximation of the set of values this expression can take at run-time.

Here is a simple C example:

introduction.c

```
1 int y, z=1;
2 int f(int x) {
```

```
3   y = x + 1;
4   return y;
5 }
6
7 void main(void) {
8   for (y=0; y<2+2; y++)
9     z=f(y);
10 }
```

If either interface of Frama-C is launched with options `-eva introduction.c`, the Eva plug-in is able to guarantee that at each passage through the `return` statement of function `f`, the global variables `y` and `z` each contain either 1 or 3. At the end of function `main`, it indicates that `y` necessarily contains 4, and the value of `z` is again 1 or 3.

When the plug-in indicates the value of `y` is 1 or 3 at the end of function `f`, it implicitly computes the union of all the values in `y` at each passage through this program point throughout any execution. In an actual execution of this deterministic program, there is only one passage though the end of function `main`, and therefore only one value for `z` at this point. The answer given by Eva is approximated but correct (the actual value, 3, is among the proposed values).

The theoretical framework on which Eva is founded is called Abstract Interpretation and has been the subject of extensive research during the last forty years.

1.2 Run-time errors and the absence thereof

An analyzed application may contain run-time errors: divisions by zero, invalid pointer accesses,...

rte.c

```
1 int i,t[10];
2
3 void main(void) {
4   for (i=0; i<=8+2; i++)
5     t[i]=i;
6 }
```

When launched with `frama-c -eva rte.c`, Eva emits a warning about an out-of-bound access at line 5:

```
[eva:alarm] rte.c:5: Warning: accessing out of bounds index. assert i < 10;
```

There is in fact an out-of-bounds access at this line in the program. It can also happen that, because of approximations during its computations, Frama-C emits warnings for constructs that do not cause any run-time errors. These are called “false alarms”. On the other hand, the fact that Eva computes correct, over-approximated sets of possible values prevents it from remaining silent on a program that contains a run-time error. For instance, a particular division in the analyzed program is the object of a warning as soon as the set of possible values for the divisor contains zero. Only if the set of possible values computed by Eva does not contain zero is the warning omitted, and that means that the divisor really cannot be null at run-time.

1.3 From Value Analysis to Eva

The Eva plug-in was previously called the *Value Analysis plug-in*. Following major changes in its expressivity and overall precision, the plugin was subsequently renamed to *Evolved Value Analysis*, or Eva for short. Those changes were first made available with the Aluminium version of Frama-C. They are presented in section 6.7.

1.4 Other analyses based on Eva

Frama-C also provides synthetic information on the behavior of analyzed functions: inputs, outputs, and dependencies. This information is computed from the results of the Eva plug-in, and therefore some familiarity with Eva is necessary to get the most of these computations.

Chapter 2

Tutorial

Some use cases for Eva...

2.1 Introduction

Throughout this tutorial, we will see on a single example how to use Eva for the following tasks :

1. to get familiar with foreign code,
2. to produce documentation automatically,
3. to search for bugs,
4. to guarantee the absence of bugs.

It is useful to stick to a single example in this tutorial, and there is a natural progression to the list of results above, but in real life, a single person would generally focus on only one or two of these four tasks for a given codebase. For instance, if you need Frama-C's help to reverse engineer the code as in tasks 1 and 2, you have probably not been provided with the quantity of documentation and specifications that is appropriate for meaningfully carrying out task 4.

Frama-C helps you to achieve tasks 1-3 in less time than you would need to get the same results using the traditional approach of writing tests cases. Task 4, formally guaranteeing the absence of bugs, can in the strictest sense not be achieved at all using tests for two reasons. Firstly, many forms of bugs that occur in a C program (including buffer overflows) may cause the behavior of the program to be non-deterministic. As a consequence, even when a test suite comes across a bug, the faulty program may appear to work correctly during tests and

fail later, after it has been deployed. Secondly, the notion of coverage of a test suite in itself is an invention made necessary because tests aren't usually exhaustive. Assume a function's only inputs are two 32-bit integers, each allowed to take the full range of their possible values. Further assume that this function only takes a billionth of a second to run (a couple of cycles on a 2GHz processor). A pencil and the back of an envelope show that this function would take 600 years to test exhaustively. Testing coverage criteria can help decide a test suite is "good enough", but there is an implicit assumption in this reasoning. The assumption is that a test suite that satisfies the coverage criteria finds all the bugs that need to be found, and this assumption is justified empirically only.

2.2 Target code: Skein-256

A single piece of code, the reference implementation for the Skein hash function, is used as an example throughout this document. As of this writing, this implementation is available at http://www.schneier.com/code/skein.zip. The Skein function is Niels Ferguson, Stefan Lucks, Bruce Schneier, Doug Whiting, Mihir Bellare, Tadayoshi Kohno, Jon Callas, and Jesse Walker's entry in the NIST cryptographic hash algorithm competition for SHA-3.

Cryptographic hash functions are one of the basic building blocks from which cryptographic protocols are designed. Many cryptographic protocols are designed with the assumption that an implementation for a function h from strings to fixed-width integers is available with the following two properties:

- it is difficult to find two distinct, arbitrary strings s_1 and s_2 such that $h(s_1) = h(s_2)$,
- for a given integer i, it is difficult to build a string s such that $h(s) = i$.

A function with the above two properties is called a cryptographic hash function. It is of the utmost importance that the function actually chosen in the implementation of a cryptographic application satisfies the above properties! Any weakness in the hash function can be exploited to corrupt the application.

Proofs of security for cryptographic hash functions are complicated mathematical affairs. These proofs are made using a mathematical definition of the function. Using static analysis for verifying that a piece of code corresponds to the mathematical model which was the object of the security proofs is an interesting topic but is outside the scope of this tutorial. In this document, we will not be using Eva for verifying cryptographic properties.

We will, however, use Eva to familiarize ourselves with Skein's reference implementation, and we will see that it can be a more useful tool than, say, a C compiler, to this effect. We will also use Eva to look for bugs in the implementation of Skein, and finally prove that the functions that implement Skein may never cause a run-time error for a general use pattern. Because of the numerous pitfalls of the C programming language, any amount of work at the mathematical level cannot exclude the possibility of problems such as buffer overflows in the implementation. It is a good thing to be able to rule these out with Eva.

Eva is most useful for embedded or embedded-like code. Although the Skein library does not exactly fall in this category, it does not demand dynamic allocation and uses few functions from external libraries, so it is well suited to this analysis.

2.3 Using Eva for getting familiar with Skein

2.3.1 Writing a test

After extracting the archive `skein_NIST_CD_010509.zip`, listing the files in `NIST/CD/Reference_Implementation` shows:

```
SHA3api_ref.c
SHA3api_ref.h
brg_endian.h
brg_types.h
skein.c
skein.h
skein_block.c
skein_debug.c
skein_debug.h
skein_port.h
```

The most natural place to go next is the file `skein.h`, since its name hints that this is the header with the function declarations that should be called from outside the library. Scanning the file quickly, we may notice declarations such as

```
typedef  struct  /*  256-bit Skein hash context structure */
    {
      [...]
    } Skein_256_Ctxt_t;

/*   Skein APIs for (incremental) "straight hashing" */
int  Skein_256_Init (Skein_256_Ctxt_t *ctx, size_t hashBitLen);
[...]
int  Skein_256_Update(Skein_256_Ctxt_t *ctx, const u08b_t *msg,
                                             size_t msgByteCnt);
[...]
int  Skein_256_Final (Skein_256_Ctxt_t *ctx, u08b_t * hashVal);
```

The impression we get at first glance is that the hash of an 80-char message containing the string "People of Earth, your attention, please" can be computed as simply as declaring a variable of type `Skein_256_Ctxt_t`, letting `Skein_256_Init` initialize it, passing `Skein_256_Update` a representation of the string, and calling `Skein_256_Final` with the address of a buffer where to write the hash value. Let us write a C program that does just that:

main_1.c

```
#include "skein.h"
#include <stdio.h>

#define HASHLEN (8)

u08b_t msg[80]="People of Earth, your attention, please";

int main(void)
{
  u08b_t hash[HASHLEN];
   int i;
  Skein_256_Ctxt_t skein_context;
  Skein_256_Init( &skein_context, HASHLEN);
```

```
14    Skein_256_Update( &skein_context, msg, 80);
15    Skein_256_Final( &skein_context, hash);
16    for (i=0; i<HASHLEN; i++)
17      printf("%d\n", hash[i]);
18    return 0;
19  }
```

In order to make the test useful, we have to print the obtained hash value. Because the result we are interested in is an 8-byte number, represented as a char array of arbitrary characters (some of them non-printable), we cannot use string-printing functions, hence the `for` loop at lines 17-18.

With luck, the compilation goes smoothly and we obtain a hash value:

```
gcc *.c
./a.out
```

```
215
215
189
207
196
124
124
13
```

Your actual result may differ from the one above; this will be explained later.

2.3.2 First try at an analysis using Eva

Let us now see how Eva works on the same example. Eva can be launched with the following command. The analysis should not take more than a few seconds:

```
frama-c -eva main_1.c >log
```

Frama-C has its own model of the target platform (the default target is a little-endian 64-bit platform). It also uses the host system's preprocessor. If you want to do the analysis for a different platform than the host platform, you need to provide Frama-C with a way to pre-process the files as they would be during an actual compilation.

There are analyses where the influence of host platform parameters is not noticeable. The analysis we are embarking on is not one of them. If you pre-process the Skein source code with a 32-bit compiler and then analyze it with Frama-C targeting its default 64-bit platform, the analysis will be meaningless and you won't be able to make sense of this tutorial. If you are using a 32-bit compiler, simply match Frama-C's target platform with your host header files by systematically adding the option `-machdep x86_32` to all commands in this tutorial.

The "`>log`" part of the command sends all the messages emitted by Frama-C into a file named "`log`". Eva is verbose for a number of reasons that will become clearer later in this tutorial. The best way to make sense of the information produced by the analysis is to send it to a log file.

There is also a Graphical User Interface for creating analysis projects and visualizing the results. Note that you cannot *edit* the source code in the GUI, only visualize it. Most of the information present in the console is also available in the GUI, but presented differently. Each interface (terminal or GUI) is better suited for a specific set of tasks.

One way to create an analysis project in the GUI is to pass the command `frama-c-gui` the same options that would be passed to `frama-c`. In this first example, the command `frama-c-gui -eva main_1.c` launches the same analysis and then opens the GUI for inspection of the results.

For simple projects like this tutorial, running everything at once is perfectly suitable; however, for larger analyses, we recommend the three-step approach presented in section 6.1.

The initial syntactic analysis and symbolic link phases of Frama-C may find issues such as inconsistent types for the same symbol in different files. Because of the way separate compilation is implemented, the issues are not detected by standard C compilers. It is a good idea to check for these issues in the first lines of the log.

2.3.3 Missing functions

Since we are trying out the library for the first time, something else to look for in the log file is the list of functions for which the source code is missing. Eva requires either a body or a specification for each function it analyzes.

```
grep "Neither code nor specification" log
```

This should match lines indicating functions that are both undefined (without source) and that have no specification in Frama-C's standard library. In our example, we obtain the following lines in the log:

```
[kernel:annot:missing-spec] main_1.c:13: Warning:
  Neither code nor specification for function Skein_256_Init,
  generating default assigns from the prototype
[eva] using specification for function Skein_256_Init
```

The same messages are produced for functions `Skein_256_Update` and `Skein_256_Final`. For each function, there are two messages: first, a warning about the absence of either code or ACSL specification for the function, stating that an *assigns* clause will be generated for the function (the *assigns* clause will be explained in detail later, in section 8.2). Second, a message stating that Eva will use a specification for the missing function.

What happens is that, without code or specification, Frama-C can only *guess* what each function does from the function's prototype, which is both inaccurate and likely incorrect. Eva needs a specification for each function without body reached during the analysis, so one is created on the fly and then used, but results are likely to be unsatisfactory.

Absence of code or ACSL specification is a major issue which often renders the analysis incorrect. For this reason, we recommend converting this warning into an error, in order to spot it immediately. The analysis scripts template*, mentioned in the Frama-C User Manual [CCK+], includes it by default.*

To fix the issue, we only need to give Frama-C all of the C sources in the directory:

```
frama-c -eva *.c >log
```

No further warnings about missing functions are emitted. We can now focus on functions without bodies:

```
grep "using specification for function" log
[eva] using specification for function printf_va_1
```

This `printf_va_1` function is not present directly in the source code; it is a specialization of a call to the variadic function `printf`. This specialization is performed by the Variadic plugin[1]. All we need to know for now is that the plugin handles calls to variadic functions and produces sound specifications for them, which are then used by Eva. This call to `printf` has no observable effects for the analysis anyway, so we do not have anything to be concerned with. It is still a good idea to check the specification of each function without body used during the analysis, since the overall correctness depends on them. This can be done using the GUI or, on the command line, with option `-print`, which outputs the Frama-C normalized source code, including ACSL specifications and transformations performed by the Variadic plugin.

It is also possible to obtain a list of missing function definitions by using the command:

```
frama-c -metrics *.c
```

This command computes, among other pieces of information, a list of missing functions (under the listing "Undefined functions") using a syntactic analysis produced by the Metrics plugin. It is not exactly equivalent to grepping the log of Eva because it lists all the functions that are missing, while the log of Eva only cites the functions that would have been necessary to an analysis. When analyzing a small part of a large codebase, the latter list may be much shorter than the former. In this case, relying on the information displayed by `-metrics` means spending time hunting for functions that are not actually necessary.

By default, Metrics does not list functions from the standard C library. This can be done by adding option `-metrics-libc`, which would produce something similar to:

```
Undefined functions (90)
========================
[...]
memcpy (21 calls); memmove (0 call); memset (27 calls); pclose (0 call);
perror (0 call); popen (0 call); printf_va_1 (1 call); putc (0 call);
```

Besides `printf_va_1`, only functions `memcpy` and `memset` are called. These functions are already specified in the Frama-C libc. However, when running Eva, they result in an output similar to the following:

```
[eva] FRAMAC_SHARE/libc/string.h:118:
  cannot evaluate ACSL term, unsupported ACSL construct: logic function memset
```

Note that this message is *not* a warning (it does not begin with the word "Warning") neither an alarm (it is not prefixed with `[eva:alarm]`). It is an informative message related to Frama-C's libc specifications that can be safely ignored[2] and will likely disappear in future Frama-C releases.

2.3.4 Interpreting the output of the analysis

By default, Eva's log emits several messages during the analysis, which are essential for a deep understanding of the issues which may happen, but on overview, these are the main components of the log:

- parsing and related messages (in our case, simply the list of files being parsed);

[1] The Variadic plugin is described in more detail in the Frama-C User Manual [CCK+].

[2] For the interested reader: some of the more thorough ACSL specifications in Frama-C's `<string.h>` are useful for plugins such as WP, but are not yet fully interpreted by Eva. Instead, Eva has builtins to correctly interpret these libc functions without only relying on their specification.

- start of the analysis by Eva, with the initial values of global variables;
- messages emitted during the analysis, such as warnings, alarms and informative feedback;
- values for all variables at the end of each function;
- an analysis summary, with coverage and the number of errors, warnings, alarms and logical properties.

If we focus on the initial values of variables, we notice that, apart from the variables defined in the source code, there is a rather strange variable named `Skein_Swap64_ONE` and containing `1`. Searching the source code reveals that this variable is in fact variable `ONE`, declared `static` inside function `Skein_Swap64`. Frama-C can display the value of static variables, something that is annoying to do when using a C compiler for testing. The GUI displays the original source code alongside the transformed one, and allows navigating between uses of a variable and its declaration.

A quick inspection shows that the Skein functions use variable `ONE` to detect endianness. Frama-C assumes a little-endian architecture by default, so Eva is only analyzing the little-endian version of the library (Frama-C also assumes an IA-64 architecture, so we are only analyzing the library as compiled and run on this architecture). The big-endian version of the library could be analyzed by reproducing the same steps we are taking here for a big-endian configuration of Frama-C.

You may also see variable names prefixed by `__fc_`, `__FC_` and `S___fc_`. These are variables coming from ACSL specifications in the Frama-C standard library.

After the initial values, the analysis log contains some lines such as:

```
[eva] skein_block.c:56: starting to merge loop iterations
```

This means that Eva has encountered a loop and is performing an approximation. These messages can be ignored for now.

Arguably some of the most important messages in the analysis are *alarms*, such as the one below:

```
[eva:alarm] skein_block.c:69: Warning:
  accessing uninitialized left-value. assert \initialized(&ks[i]);
```

As we will find out later in this tutorial, this alarm is a false alarm, an indication of a potential problem in a place where there is in fact none. However, Eva never remains silent when a risk of run-time error is present, unlike many other static analysis tools. The important consequence is that if you get the tool to remain silent, you have *formally verified* that no run-time error could happen when running the program.

The alarm means that Eva could not prove that the value `ks[i]` accessed in `skein_block.c:69` was definitely initialized before being read. Reading an uninitialized value is an undefined behavior according to the C99 standard (and can even lead to security vulnerabilities).

As is often the case, this alarm is related to the approximation introduced in `skein_block.c:56`, which is the loop responsible for initializing the values of array `ks[i]`. The order of the messages during the analysis thus provides some hints about what is happening, and also some ideas about how to solve them.

2.3.5 Increasing analysis precision in loops

The previous alarm is just one of several related to variable initialization. Before we spend any of our time looking at each of these alarms, trying to determine whether they are true or false, it is a good idea to make the analyzer spend more of *its* time trying to determine the same thing. There are different settings that influence the trade-off between precision and resource consumption.

When dealing with bounded loops, option `-eva-auto-loop-unroll N` automatically unrolls simple loops that have less than `N` iterations. This option is based on syntactic heuristics to improve the precision at a low cost, and will not handle complex loops. It should be enabled in most analyses.

If automatic loop unrolling is insufficient, the next best approach consists in using an ACSL annotation, `//@ loop unroll N`, to direct Eva to analyze precisely the `N` first iterations of the loop before approximating the results.

Note: both approaches can be combined to enable automatic loop unrolling *except* in a few chosen loops: since the `@loop unroll` annotation takes precedence over other options, adding `@loop unroll 0;` to a loop will prevent it from being unrolled, even when `-eva-auto-loop-unroll` is active.

Frama-C's graphical interface can help estimating loop bounds by inspecting the values taken by the loop counter, as in the example below:

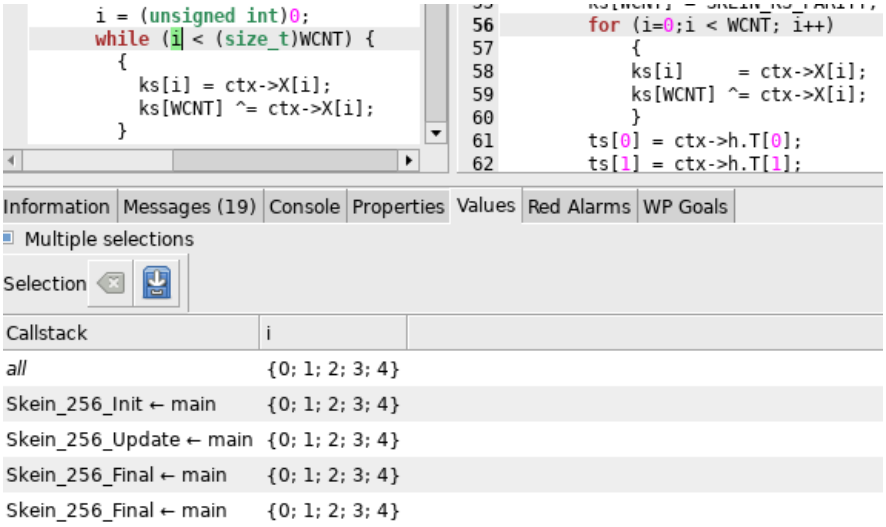


Figure 2.1: Estimating loop unroll bounds in the GUI

In this case, `WCNT` has a constant value (4), so it could also be used to estimate the loop bounds.

We can then Ctrl+click on the loop condition in the original source view (right panel) to open an editor[3] centered on the loop, and then add the loop unroll annotation, as follows:

```
//@ loop unroll 4;
for (i=0;i < WCNT; i++)
    {
    ks[i]    = ctx->X[i];
    ks[WCNT] ^= ctx->X[i];         /* compute overall parity */
```

[3]The external code editor used by the GUI can be defined via the menu *File - Preferences*.

```
    }
```

The value 4 is sufficient to completely unroll the loop, even though `i` ranges from 0 to 4 (5 values in total). One way to confirm the unrolling is complete is to check that "starting to merge loop iterations" is no longer emitted when entering the loop. Also, when a loop unroll annotation is present but insufficient to unroll the loop, a message is emitted:

```
[eva:loop-unroll] skein_block.c:57: loop not completely unrolled
```

Once a loop is completely unrolled, any "leftovers" are ignored, so it incurs no extra cost. Using a value larger than necessary is therefore not an issue.

The practical effect of adding this annotation and then re-running Eva is the elimination of 3 alarms in the analysis. Thanks to the extra precision allowed by the annotation (with a minimal increase in analysis time), Eva is now able to prove there are no initialization errors in more places than before.

2.3.6 Increasing precision

Option `-eva-precision` allows setting a global trade-off between precision and analysis time. By default, Eva is tuned to a low precision to ensure a fast initial analysis. Especially for smaller code bases, it is often useful to increase this precision, to dismiss "easy" alarms. Precision can be set between 0 and 11, the higher the value, the more precise the analysis. The default value of Eva is somewhere between 0 and 1, so that setting `-eva-precision 0` potentially allows it to go even faster (only useful for large or very complex code bases).

`-eva-precision` is in fact a meta-option, whose only purpose is to set the values of other options to a set of predefined values. This avoids the user having to know all of them, and which values are reasonable. Think of it as a "knob" to perform a coarse adjustment of the analysis, before fine-tuning it more precisely with other options.

`-eva-precision` displays a message when it is used, stating which options are affected and the value given to them. If one of those options is already specified by the user, that value takes priority over the one chosen by `-eva-precision`.

Among the options set by `-eva-precision`, there is `-eva-slevel`, which can be thought of as some kind of "fuel" to be consumed during the analysis: as long as there is some slevel, the analysis will keep states separated and maintain precision at the cost of extra analysis time; when all of it is consumed, further states are merged, avoiding increase in analysis time but approximating the results. It can also be specified separately for each function (`-eva-slevel-function f:n`).

For complex code bases, however, `-eva-slevel` lacks in stability and predictability: it is very hard to determine exactly *how* it is used. It can be consumed in the presence of loops, branches, disjunctions; in nested loops, it is consumed by both inner and outer loops. In loops with branches, its consumption may become exponential. And once a satisfactory value is found, later changes to the source code, ACSL specifications, Eva's algorithms or other parameters can affect it, requiring a new parametrization.

In our example, we can quickly try a few values of `-eva-precision`, such as 1, 2 and 3:

```
frama-c -eva-precision 3 -eva *.c >log
```

Now, the analysis goes rather far without finding any alarm, but when it is almost done (after the analysis of function `Skein_256_Final`), it produces:

```
...
[eva] using specification for function printf_va_1
[eva:alarm] main_1.c:17: Warning:
  accessing uninitialized left-value. assert \initialized(&hash[i]);
[eva] done for function main
...
```

There remains an alarm about initialization, but all the others have been removed. Trying larger values for precision or slevel does not change this. In this case, we can afford to spend some time looking at it in more detail.

2.3.7 Inspecting alarms in the GUI

Instead of running `frama-c`, let us use `frama-c-gui`:

```
frama-c-gui -eva-precision 3 -eva *.c >log
```

The GUI allows the user to navigate the source code, to inspect the sets of values inferred by the analysis and to get a feeling of how it works. Right-clicking on the function name at a call site brings a contextual menu to jump to the function's definition. In order to return to the caller, right-clicking on the name of the current function at the top brings a contextual menu with a list of callers. You can also use the Back button (left arrow) in the toolbar. The Information panel also offers navigation possibilities between variables and their definitions.

In the graphical interface, three panels (displayed below the source code) are very useful for Eva: Properties, Values, and Red Alarms. Further details about the GUI are presented in chapter 4. For now, it suffices to say that:

- Properties displays (among others) the list of alarms in the program;
- Values displays the inferred values for the expression selected in the Frama-C normalized source code (highlighted in green);
- Red Alarms displays some special cases of alarms that should be considered first.

In the GUI, each alarm is represented with a "bullet" to its left. Red bullets mean "this *always* happens"; yellow bullets mean "this *may* happen (but I am not sure, due to approximations)". When there are several alarms, some strategies allow prioritizing which alarms are more likely to correspond to actual issues.

The overall rule of thumb when inspecting alarms in the GUI[4] is the following:

- inspect red alarms in the Properties panel; these correspond to situations where the analysis is *certain* that a problem has arrived; either an actual bug in the code, or some issue in the analysis that needs to be addressed (e.g. due to missing or incorrect specifications);
- inspect the cases present in the Red Alarms panel; these are situations which are likely to correspond to definitive problems, and thus should be treated before others[5];

[4]The first time the Frama-C GUI is run, the Properties panel displays several kinds of properties. For Eva, the most useful view consists in selecting the "Reset 'Status' filters to show only unproved/invalid" option, using the button next to "Refresh" in the Properties panel.

[5]The *exact* meaning of such red alarms is too complex to be presented here; as a first approximation, these can be seen as intermediate between red and yellow alarms.

- inspect remaining cases (yellow alarms) in the Properties panel.

In the case of our remaining alarm, it is yellow, but it appears in the Red Alarms panel. This indicates it is more likely to correspond to a real issue.

Extra information can be observed by clicking the alarm in the Red Alarms tab, which highlights it in the source code, then selecting expression `hash` in line 17 and reading the Values tab:

```
[0] ∈ {200}
[1..7] ∈ UNINITIALIZED
```

This means that element `hash[0]` has value 200, but elements 1 to 7 are definitely uninitialized. Therefore the first iteration of the loop proceeds as expected, but on the second iteration, the analysis of the branch is stopped, because from the point of view of the analyzer, reading an uninitialized value should be a fatal error. And there are no other execution branches that reach the end of this loop, which is why the analyzer finds that function `main` does not terminate (the log contains the message "NON TERMINATING FUNCTION").

2.3.8 Finding and fixing bugs

We found a real issue in the code, but to find the exact cause it is necessary to investigate the code. Looking again at the header file `skein.h`, we may now notice that in function `Skein_256_Init`, the formal parameter for the desired hash length is named `hashBitLen`. This parameter should certainly be expressed in bits! We were inadvertently asking for a 1-char hash of the message since the beginning, and the test that we ran as our first step failed to notice it.

The bug can be fixed by passing 8*HASHLEN instead of HASHLEN as the second argument of `Skein_256_Init`. With this fix in place, the analysis with `-eva-precision 3` produces no alarms and gives the following result:

```
Values for function main:
  hash[0] ∈ {40}
      [1] ∈ {234}
      [2] ∈ {138}
      [3] ∈ {230}
      [4] ∈ {134}
      [5] ∈ {120}
      [6] ∈ {37}
      [7] ∈ {35}
  i ∈ {8}
```

Meanwhile, compiling and executing the fixed test produces the result:

```
40
234
138
230
134
120
37
35
```

2.4 Guaranteeing the absence of bugs

2.4.1 Generalizing the analysis to arbitrary messages of fixed length

The analysis we have done so far is very satisfying because it finds problems that are not detected by a C compiler or by testing. The results of this analysis only prove the absence of run-time errors[6] when the particular message that we chose is being hashed, though. It would be much more useful to have the assurance that there are no run-time errors for any input message, especially since the library might be under consideration for embedding in a device where anyone (possibly a malicious user) will be able to choose the message to hash.

A first generalization of the previous analysis is to include in the subject matter the hashing of all possible 80-character messages. We can do this by separating the analyzed program in two distinct phases, the first one being the construction of a generalized analysis context and the second one being made of the sequence of function calls that we wish to study:

main_2.c

```
1  #include "skein.h"
2  #include "__fc_builtin.h"
3
4  #define HASHLEN (8)
5
6  u08b_t msg[80];
7
8  int Frama_C_interval(int,int);
9
10 void main(void)
11 {
12   int i;
13   u08b_t hash[HASHLEN];
14   Skein_256_Ctxt_t skein_context;
15
16   for (i=0; i<80; i++) msg[i]=Frama_C_interval(0, 255);
17
18   Skein_256_Init( &skein_context, HASHLEN * 8);
19   Skein_256_Update( &skein_context, msg, 80);
20   Skein_256_Final( &skein_context, hash);
21 }
```

From this point onward the program is no longer executable because of the call to builtin primitives such as `Frama_C_interval`. We therefore dispense with the final calls to `printf`, since Eva offers simpler ways to observe intermediate and final results. Note that we included `__fc_builtin.h`, a file that comes from the Frama-C distribution and which defines `Frama_C_interval`. Running Frama-C on this file (without `main_1.c` in the same directory, to avoid having two definitions for `main`):

```
frama-c -eva-precision 3 -eva *.c >log 2>&1
```

This time, the absence of actual alarms is starting to be really interesting: it means that it is formally excluded that the functions `Skein_256_Init`, `Skein_256_Update`, and `Skein_256_Final` produce a run-time error when they are used, in this order, to initialize a local variable of type

[6] and the absence of conditions that *should* be run-time errors – like the uninitialized access already encountered

`Skein_256_Ctxt_t` (with argument 64 for the size), parse an arbitrary message and produce a hash in a local `u08b_t` array of size 8.

2.4.2 Verifying functional dependencies

If we had written a formal specification for function Skein, we would soon have expressed that we expected it to modify the buffer `hash` that is passed to `Skein_256_Final` (all 8 bytes of the buffer), to compute the new contents of this buffer from the contents of the input buffer `msg` (all 80 bytes of it), and from nothing else.

During Eva's analysis, we have seen that all of the buffer `hash` was always modified in the conditions of the analysis: the reason is that this buffer was uninitialized before the sequence of calls, and guaranteed to be initialized after them.

We can get the complete list of locations that may be modified by each function by adding the option `-out` to the other options we were already using. These locations are computed in a quick analysis that comes after Eva. In the results of this analysis, we find:

```
[inout] Out (internal) for function main:
         Frama_C_entropy_source; msg[0..79]; i; hash[0..7]; skein_context; tmp
```

The "(internal)" reminds us that this list includes the local variables of `main` that have been modified. Indeed, all the variables that we could expect to appear in the list are here: the input buffer, that we initialized to all possible arbitrary 80-char messages; the loop index that we used in doing so; the output buffer for receiving the hash; and Skein's internal state, that was indirectly modified by us when we called the functions `Init`, `Update` and `Final`.

If we want the outputs of the sequence to appear more clearly, without the variables we used for instrumenting, we can put it in its own function:

```
1  u08b_t hash[HASHLEN];
2
3  void do_Skein_256(void)
4  {
5    Skein_256_Ctxt_t skein_context;
6    Skein_256_Init( &skein_context, HASHLEN * 8);
7    Skein_256_Update( &skein_context, msg, 80);
8    Skein_256_Final( &skein_context, hash);
9  }
10
11 void main(void)
12 {
13   int i;
14
15   for (i=0; i<80; i++) msg[i]=Frama_C_interval(0, 255);
16
17   do_Skein_256();
18 }
```

Using option `-out-external` in order to obtain lists of locations that exclude each function's local variables, we get:

```
[inout] Out (external) for function do_Skein_256:
         hash[0..7]
```

This means that no location other than `hash[0..7]` was modified by the sequence of calls to Skein-256 functions. It doesn't mean that each of the cells of the array was overwritten:

we have to rely on the results of Eva when `hash` was a local variable for that result. But it means that when used in conformance with the pattern in this program, the functions do not accidentally modify a global variable. We can conclude from this analysis that the functions are re-entrant as long as the concurrent computations are being made with separate contexts and destination buffers.

Keeping the convenient function `do_Skein_256` for modeling the sequence, let us now compute the functional dependencies of each function. Functional dependencies list, for each output location, the input locations that influence the final contents of this output location:

```
frama-c -eva *.c -eva-precision 3 -deps
```

```
Function Skein_256_Init:
  skein_context.h.hashBitLen FROM ctx; hashBitLen
              .h{.bCnt; .T[0..1]; } FROM ctx
              .X[0..3] FROM msg[0..63];
                           skein_context{.X[0..3]; .b[0..31]; }; ctx;
                           hashBitLen; Skein_Swap64_ONE[bits 0 to 7] (and SELF)
              .b[0..31] FROM ctx (and SELF)
  \result  FROM \nothing

Function Skein_256_Update:
  skein_context.h.bCnt FROM skein_context.h.bCnt; ctx; msgByteCnt
              .h.T[0] FROM skein_context.h{.bCnt; .T[0]; }; ctx; msgByteCnt
              .h.T[1] FROM skein_context{.h.bCnt; .h.T[1]; }; ctx;
                           msgByteCnt
              {.X[0..3]; .b[0..15]; } FROM msg[0..79];
                                          skein_context{.h{.bCnt; .T[0..1]; };
                                                        .X[0..3]; .b[0..31]; };
                                           ctx; msg_0; msgByteCnt (and SELF)
  \result  FROM \nothing

Function Skein_256_Final:
  hash[0..7] FROM msg[0..79]; skein_context; ctx;
                 hashVal; Skein_Swap64_ONE[bits 0 to 7] (and SELF)
  skein_context.h.bCnt FROM skein_context.h.hashBitLen; ctx (and SELF)
              .h.T[0] FROM skein_context.h{.hashBitLen; .bCnt; .T[0]; }; ctx
              .h.T[1] FROM skein_context{.h.hashBitLen; .h.T[1]; }; ctx
              {.X[0..3]; .b[0..15]; } FROM msg[0..79]; skein_context;
                                          ctx; Skein_Swap64_ONE[bits 0 to 7] (and SELF)
              .b[16..31] FROM skein_context.h.bCnt; ctx (and SELF)
  \result  FROM \nothing
```

The functional dependencies for the functions `Init`, `Update` and `Final` are quite cryptic. They refer to fields of the struct `skein_context`. We have not had to look at this struct yet, but its type `Skein_256_Ctxt_t` is declared in file `skein.h`.

In the results, the mention `(and SELF)` means that parts of the output location may keep their previous values. Conversely, absence of this mention means that the output location is guaranteed to have been completely over-written when the function returns. For instance, the field `skein_context.h.T[0]` is guaranteed to be over-written with a value that depends only on various other subfields of `skein_context.h`. On the other hand, the `-deps` analysis does not guarantee that all cells of `hash` are over-written — but we previously saw we could deduce this information from Eva's results.

Since we don't know how the functions are supposed to work, it is difficult to tell if these

dependencies are normal or reveal a problem. Let us move on to the functional dependencies of `do_Skein_256`:

```
Function do_Skein_256:
  hash[0..7] FROM msg[0..79]; Skein_Swap64_ONE[bits 0 to 7] (and SELF)
```

These dependencies make the effect of the functions clearer. The `FROM msg[0..79]` part is what we expect. The `and SELF` mention is an unfortunate approximation. The dependency on global variable `Skein_Swap64_ONE` reveals an implementation detail of the library (the variable is used to detect endianness dynamically). Finding out about this variable is a good thing: it shows that a possibility for a malicious programmer to corrupt the implementation into hashing the same message to different digests would be to try to change the value of `Skein_Swap64_ONE` between computations. Checking the source code for mentions of variable `Skein_Swap64_ONE`, we can see it is used to detect endianness and is declared `const`. On an MMU-equipped platform, there is little risk that this variable could be modified maliciously from the outside. However, this is a vivid example of how static analysis, and especially correct analyses as provided in Frama-C, can complement code reviews in improving trust in existing C code.

Assuming that variable `Skein_Swap64_ONE` keeps its value, a same input message is guaranteed always to be hashed by this sequence of calls to the same digest, because option `-deps` says that there is no other memory location `hash` is computed from, not even an internal state.

A stronger property to verify would be that the sequence `Init(...)`, `Update(...,80)`, `Final(...)` computes the same hash as when the same message is passed in two calls `Update(...,40)`. This property is beyond the reach of Eva. In the advanced tutorial, we show how to verify easier properties for sequences of calls that include several calls to `Update`.

2.4.3 Generalizing to arbitrary numbers of Update calls

As an exercise, try to verify that there cannot be a run-time error when hashing arbitrary contents by calling `Update(...,80)` an arbitrary number of times between `Init` and `Final`. The general strategy is to modify the C analysis context we have already written in a way such that it is evident that it captures all such sequences of calls, and also in a way that launched with adequate options, Eva does not emit any warning.

The latter condition is harder than the former. Observing results (with the GUI or observation functions described in section 9.3) can help to iterate towards a solution. Be creative. The continuation of this tutorial can be found online at http://blog.frama-c.com/index.php?tag/skein[7] ; read available posts in chronological order.

[7] Note that some messages and options have changed since the tutorial was posted. Using an older Frama-C version may be necessary to obtain similar results.

Chapter 3

What Eva provides

Here begins the reference section of this manual.
This chapter categorizes and describes the outputs of Eva.

3.1 Values

The Eva plug-in accepts queries for the value of a variable `x` at a given program point. It answers such a query with an over-approximation of the set of values possibly taken by `x` at the designated point for all possible executions.

3.1.1 Variation domains for expressions

The variation domain of a variable or expression can take one of the shapes described below.

A set of integers

The analyzer may have determined the variation domain of a variable is a set of integers. This usually happens for variables of an integer type, but may happen for other variables if the application contains unions or casts. A set of integers can be represented as:

- an enumeration, `{`v_1; ... v_n`}`,
- an interval, `[`l..u`]`, that represents all the integers comprised between l and u. If "`--`" appears as the lower bound l (resp. the upper bound u), it means that the lower bound (resp upper bound) is $-\infty$ (resp. $+\infty$),
- an interval with periodicity information, `[`l..u`],`r`%`m, that represents the set of values comprised between l and u whose remainder in the Euclidean division by m is equal to r. For instance, `[2..42],2%10`, represents the set that contains 2, 12, 22, 32, and 42.

A floating-point value or interval

A location in memory (typically a floating-point variable) may also contain a floating-point number or an interval of floating-point numbers:

- f for the non-zero floating-point number f (the floating-point number `+0.0` has the same representation as the integer `0` and is identified with it),
- `[`f_l `..` f_u`]` for the interval from f_l to f_u inclusive.

A set of addresses

A variation domain (for instance for a pointer variable) may be a set of addresses, denoted by `{{`a_1; ... a_n`}}`. Each a_i is of the form:

- $\&x + D$, where $\&x$ is the base address corresponding to the variable x, and D is in the domain of integer values and represents the possible offsets **expressed in bytes** with respect to the base address $\&x$. When x is an array or an aggregate, and D corresponds to the offset(s) of a field or an array cell, a concrete C-like syntax may be used, i.e. `&t{[1].i1, [2].i2}`.
- `NULL` $+ D$, which denotes absolute addresses (seen as offsets with respect to the base address NULL).
- `"foo"` $+ D$, which denotes offsets from a literal string with contents "foo".

In all three cases, " $+ D$" is omitted if D is $\{0\}$, that is, when there is no offset.

An imprecise mix of addresses

If the application involves, or seems to involve, unusual arithmetic operations over addresses, many of the variation domains provided by the analysis may be imprecise sets of the form `garbled mix of` $\&\{x_1; \ldots x_n\}$. This expression denotes an unknown value built from applying arithmetic operations to the addresses of variables x_1,...,x_n and to integers.

Absolutely anything

You should not observe it in practice, but sometimes the analyzer is not able to deduce any information at all on the value of a variable, in which case it displays `ANYTHING` for the variation domain of this variable.

3.1.2 Memory contents

Memory locations can contain, in addition to the above sets of values, uninitialized data and dangling pointers. It is illegal to use these special values in computations, which is why they are not listed as possible values for an expression. Reading from a variable that appears to be uninitialized causes an alarm to be emitted, and then the set of values for the variable is made of those initialized values that were found at the memory location.

3.1.3 Interpreting the variation domains

Most modern C compilation platforms unify integer values and absolute addresses: there is no difference between the encoding of the integer 256 and that of the address `(char*)0x00000100`. Therefore, Eva does not distinguish between these two values either. It is partly for this reason that offsets D are expressed in bytes in domains of the form `{{`$\&x + D$`; ... }}`.

Examples of variation domains

- `{3, 8, 11}` represents exactly the integers 3, 8 and 11.
- `[1..256]` represents the set of integers comprised between 1 and 256, each of which can also be interpreted as an absolute address between 0x1 and 0x100.
- `[0..256],0%2` represents the set of even integers comprised between 0 and 256. This set is also the set of the addresses of the first 129 aligned 16-bit words in memory.
- `[1..255],1%2` represents the odd integers comprised between 1 and 255.
- `[--..--]` represents the set of all (possibly negative) integers that fit within the type of the variable or expression that is being printed.
- `{3.}` represents the floating-point number `3.0`.
- `[-3. .. 9.]` represents the interval of floating-point values comprised between `-3.0` and `9.0`.
- `[-3. .. 9.]` ∪ `{NaN}` represents the same interval as above, plus `NaN`.
- `[-inf .. 3.4]` represents the interval of floating-point values comprised between $-\infty$ and `3.4`.
- `[-inf .. inf]` ∪ `{NaN}` represents all possible floating-point values.
- `{{ &x }}` represents the address of the variable `x`.
- `{{ &x + { 0; 1 } }}` represents the address of one of the first two bytes of variable `x` – assuming `x` is of a type at least 2 bytes in size. Otherwise, this notation represents a set containing the address of `x` and an invalid address.
- `{{ &x ; &y }}` represents the addresses of `x` and `y`.
- `{{ &t + [0..256],0%4 }}`, in an application where `t` is declared as an array of 32-bit integers, represents the addresses of locations `t[0]`, `t[1]`, ..., `t[64]`.
- `{{ &t + [0..256] }}` represents the same values as the expression `(char*)t+i` where the variable `i` has an integer value comprised between 0 and 256.
- `{{ &t + [--..--] }}` represents all the addresses obtained by shifting `t`, including some misaligned and invalid ones.

3.1.4 Origins of approximations

Approximated values may contain information about the origin of the approximations. In this case the value is shown as "`garbled mix of &{`x_1`; ... `x_n`} (origin: ...)`". The text provided after "`origin:`" indicates the location and the cause of some of these approximations.

Most origins are of the form `Cause L`, where `L` is an (optional) line or the application indicating where the approximation took place. Origin causes are one of the following:

Misaligned read

The origin `Misaligned L` indicates that misaligned reads prevented the computation to be precise. A misaligned read is a memory read-access where the bits read were not previously written as a single write that modified the whole set of bits exactly.

An example of a program leading to a misaligned read is the following:

```
1 int x,y;
2 int *t[2] = { &x, &y };
3
4 int main(void)
5 {
6   return * (int*) ((unsigned long) t + 6);
7 }
```

The value returned by the function `main` is
`{{ garbled mix of &{ x; y } (origin: Misaligned { misa.c:6 }) }}`.
The analyzer is by default configured for a 64-bit architecture, and that consequently the read memory access is not an out-of-bound access. If it was, an alarm would be emitted, and the analysis would go in a different direction.

With the default target platform, the read access remains within the bounds of array `t`, but due to the offset of six bytes, the 32-bit word read is made of the last two bytes from `t[0]` and the first two bytes from `t[1]`.

Call to an unknown function

The origin `Library function L` arises from the interpretation of a function specification, when an `assigns` clause applies to pointer values. A function specification is only used for:

- functions whose body is not provided, and for which no Eva builtins exist. See section 9.4 for a list of available builtins.
- recursive functions that cannot be completely analyzed; see section 6.3.9 for more details.
- functions given to the `-eva-use-spec` option; see section 6.3.10 for more details.

Fusion of values with different alignments

The notation `Merge L` indicates that memory states with incompatible alignments are fused together. In the example below, the memory states from the then branch and from the else branch contain in the array `t` some 32-bit addresses with incompatible alignments.

```
1 int x,y;
2 char t[8];
3
4 int main(int c)
5 {
6   if (c)
7     * (int**) t = &x;
8   else
9     * (int**) (t+2) = &y;
```

```
10    x = t[2];
11    return x;
12  }
```

The value returned by function `main` is
`{{ garbled mix of &{ x; y } (origin: Merge { merge.c:10 }) }}`.

Well value

When generating an initial state to start the analysis from (see section 6.3.3 for details), the analyzer has to generate a set of possible values for a variable with only its type for information. Some recursive or deeply chained types may force the generated contents for the variable to contain imprecise, absorbing values called well values.

Computations that are imprecise because of a well value are marked as `origin: Well`.

Arithmetic operation

The origin `Arithmetic L` indicates that arithmetic operations take place without the analyzer being able to represent the result precisely.

```
1  int x,y;
2  int f(void)
3  {
4    return (int) &x + (int) &y;
5  }
```

In this example, the return value for `f` is
`{{ garbled mix of &{ x; y } (origin: Arithmetic { ari.c:4 }) }}`.

3.2 What is checked by Eva

Eva warns about possible run-time errors in the analyzed program, through the means of *proof obligations*: the errors that cannot be proved by the Eva plug-in are left to be proved by other plug-ins. These proof obligations are displayed as messages that contain the word assert in the textual log. Within Frama-C's AST, they are also available ACSL predicates. (Frama-C comes with a common specification language for all plug-ins, called ACSL, described at http://frama-c.com/acsl.html.)

When using the GUI version of Frama-C, proof obligations are inserted in the normalized source code. With the batch version, option `-print` produces a version of the analyzed source code annotated with the proofs obligations. The companion option `-ocode <file.c>` allows to specify a filename for the annotated source code to be written to.

Invalid memory accesses

Whenever Eva is not able to establish that a dereferenced pointer is valid, it emits an alarm that expresses that the pointer needs to be valid at that point. Likewise, direct array accesses that may be invalid are flagged.

```
1  int i, t[10], *p;
2  void main()
3  {
4    for (i=0; i<=10; i++)
```

```
5       if (unknownfun()) t[i] = i;
6     p = t + 12;
7      if (unknownfun()) *p = i;
8     p[-6] = i;
9   }
```

In the above example, the analysis is not able to guarantee that the memory accesses `t[i]` and `*p` are valid, so it emits a proof obligation for each:

```
invalid.c:5: ... accessing out of bounds index. assert i < 10;
invalid.c:7: ... out of bounds write. assert \valid(p);
```

(Notice that no alarm `assert 0 <= i` is emitted, as the analysis is able to guarantee that this always holds.)

The choice between these two kinds of alarms is influenced by option `-unsafe-arrays`, as described page 77.

Note that line 6 or 8 in this example could be considered as problematic in the strictest interpretation of the standard. Eva omits warnings for these two lines according to the attitude described in 5.5.1. An option to warn about these lines could happen if there was demand for this feature.

Invalid pointer arithmetic

By default, Eva does *not* emit alarms on invalid pointer arithmetic: alarms are only emitted when an invalid pointer is dereferenced or wrongly used in a comparison, not at the creation of such pointers.

However, if the `-warn-invalid-pointer` option is enabled, Eva emits an alarm when an operation may create a pointer that does not point inside an object or one past an object, even if this pointer is not used afterward.

This may happen on:

- addition (or subtraction) of an integer from a pointer, when the analysis is unable to prove that the resulting pointer points inside, or one past, the same object pointed to by the initial pointer. In this case, the emitted alarm reports a possible undefined behavior.
- conversion of an integer into a pointer. Except for the constant 0, such a conversion is always an implementation-defined behavior according to the C99 standard. However, a footnote also explains that conversion between pointers and integers is "*intended to be consistent with the addressing structure of the execution environment*". This is why Eva also authorizes conversion of integers:
  - ▷ in the range of valid absolute addresses (according to `absolute-valid-range`)
  - ▷ computed from the address of an object `o` such that the resulting pointer points inside or one past the object `o`.

  In all other cases, an alarm is emitted, which reports the possible implementation-defined behavior mentioned above.

In the example below, the first increment of the pointer `p` is valid, although the resulting pointer should not be dereferenced. The second increment leads to an invalid alarm when option `-warn-invalid-pointer` is on.

```
1 void main () {
2   int x, *p = &x;
3   p++;
4   p++;
5 }
```

```
[eva:alarm] pointer_arith.c:4: Warning:
  invalid pointer creation. assert \object_pointer(p + 1);
```

In the same way, in the example below, the first conversion at line 5 does not generate an alarm, but the second conversion leads to an invalid alarm with option `-warn-invalid-pointer`.

```
1 #include <stdint.h>
2 void main () {
3   char c;
4   uintptr_t a = &c;
5   char *p = (char *) (a + 1);
6   char *q = (char *) (a + 2);
7 }
```

```
[eva:alarm] pointer_arith.c:6: Warning:
  invalid pointer creation. assert \object_pointer((char *)(a + 2));
```

Division by zero

When dividing by an expression that the analysis is not able to guarantee non-null, a proof obligation is emitted. This obligation expresses that the divisor is different from zero at this point of the code.

In the particular case where zero is the only possible value for the divisor, the analysis stops the propagation of this execution path. If the divisor seems to be able to take non-null values, the analyzer is allowed to take into account the property that the divisor is different from zero when it continues the analysis after this point. The property expressed by an alarm may also not be taken into account when it is not easy to do so.

```
1 int A, B;
2 void main(int x, int y)
3 {
4   A = 100 / (x * y);
5   B = 333 % x;
6 }
```

```
div.c:4: ... division by zero. assert (int)(x*y) != 0;
div.c:5: ... division by zero. assert x != 0;
```

In the above example, there is no way for the analyzer to guarantee that `x*y` is not null, so it emits an alarm at line 4. In theory, it could avoid emitting the alarm `x != 0` at line 5 because this property is a consequence of the property emitted as an alarm at line 4. Redundant alarms happen – even in cases simpler than this one. Do not be surprised by them.

Undefined logical shift

Another arithmetic alarm is the alarm emitted for logical shift operations on integers where the second operand may be larger than the size in bits of the first operand's type. Such an operation is left undefined by the C99 standard, and indeed, processors are often built in a way that such an operation does not produce the `0` or `-1` result that could have been expected. Here is an example of program with such an issue, and the resulting alarm:

```
1 void main(int c){
2   int x;
3   c = c ? 1 : 8 * sizeof(int);
4   x = 1 << c;
5 }
```

```
shift .c:4: ... invalid RHS operand for shift. assert 0 <= c < 32;
```

Eva also detects shifts on negative integers. Left-shifting a negative integer is an undefined behavior according to the C99 standard, and leads to an alarm by default. These alarms can be disabled by using the option `-no-warn-left-shift-negative`. Right-shifting a negative integer is an implementation-defined operation, and does not lead to an alarm by default. However, the option `-warn-right-shift-negative` can be used to enable such alarms.

```
1 void main(int c){
2   int x;
3   x = -7,
4   x = x << 2;
5 }
```

```
[eva:alarm] lshift.c:4: Warning: invalid LHS operand for left shift. assert 0 <= x;
```

Overflow in integer arithmetic

By default, Eva emits alarms for — and reduces the sets of possible results of — signed arithmetic computations where the possibility of an overflow exists. Indeed, such overflows have an undefined behavior according to paragraph 6.5.5 of the C99 standard. If useful, it is also possible to assume that signed integers overflow according to a 2's complement representation. The option `-no-warn-signed-overflow` can be used to this end. A reminder warning is nevertheless emitted on operations that are detected as potentially overflowing. This warning can also be disabled by option `-eva-warn-key signed-overflow=inactive`.

By default, no alarm is emitted for arithmetic operations on unsigned integers for which an overflow may happen, since such operations have defined semantics according to the C99 standard. If one wishes to signal and prevent such unsigned overflows, option `-warn-unsigned-overflow` can be used.

By default, Eva emits alarms for downcasts of pointer values to (signed or unsigned) integer types. Such downcasts are indeed undefined behavior according to section 6.3.2.3, §6 of the C99 standard. However, option `-no-warn-pointer-downcast` can be used to disable these alarms.

Finally, by default, no alarm is emitted for downcasts to signed or unsigned integers. In the signed case, the least significant bits of the original value are used, and are interpreted according to 2's complement representation. Frama-C's options `-warn-signed-downcast` and `-warn-unsigned-downcast` can be used to emit alarms on signed or unsigned downcasts that may exceed the destination range.

Overflow in conversion from floating-point to integer

An alarm is emitted when a floating-point value appears to exceed the range of the integer type it is converted to.

```
1 #include "__fc_builtin.h"
2
```

```
int main()
{
  float f = Frama_C_float_interval(2e9, 3e9);
  return (int) f;
}
```

```
...
[eva:alarm] ov_float_int.c:6: Warning: overflow in conversion from floating-point
 to integer. assert f < 2147483648;

[eva] Values at end of function main:
f ∈ [2000000000. .. 3000000000.]
__retres ∈ [2000000000..2147483647]
```

Floating-point alarms

By default, Eva emits an alarm whenever a floating-point operation can result in a `NaN` or infinite value, and continues the analysis with a finite interval representing the result obtained if excluding these possibilities. This interval, like any other result, may be over-approximated. An example of this first kind of alarm can be seen in the following example.

```
double sum(double a, double b)
{
  return a+b;
}
```

```
frama-c -eva -main sum double_op_res.c
```

```
[eva:alarm] double_op_res.c:3: Warning: non-finite double value.
    assert \is_finite((double)(a+b));
```

An alarm is also emitted when the program uses as argument to a floating-point operation a value from memory that does not ostensibly represent a floating-point number. This can happen with a union type with both `int` and `float` fields, or in the case of a conversion from `int*` to `float*`. The emitted alarm excludes the possibility of the bit sequence used as a the argument representing `NaN`, an infinite, or an address. See the example below.

```
union { int i ; float f ; } bits;

float r;

int main () {
  bits.i = unknown_fun();
  r = 1.0 + bits.f;
  return r > 0.;
}
```

```
frama-c -eva double_op_arg.c
```

```
[eva:alarm] double_op_arg.c:7: Warning: non-finite float value.
    assert \is_finite(bits.f);
```

These floating-point alarms can be disabled — thus allowing `NaN` and infinite values for the analysis — by setting the `-warn-special-float` option:

- `-warn-special-float non-finite`: `NaN` and infinite values are forbidden. This is the default mode of Eva.
- `-warn-special-float nan`: only `NaN` are forbidden; infinite values are allowed, and do not raise alarms.
- `-warn-special-float none`: both `NaN` and infinite values are allowed: they are simply propagated during the analysis, without leading to special alarms.

Uninitialized variables and dangling pointers to local variables

An alarm may be emitted if the application appears to read the value of a local variable that has not been initialized, or if it appears to manipulate the address of a local variable outside of the scope of said variable. Both issues occur in the following example:

```
1  int *f(int c)
2  {
3    int r, t, *p;
4    if (c) r = 2;
5    t = r + 3;
6    return &t;
7  }
8
9  int main(int c)
10 {
11   int *p;
12   p = f(c);
13   return *p;
14 }
```

Eva emits alarms for lines 5 (variable `r` may be uninitialized) and 13 (a dangling pointer to local variable `t` is used).

```
uninitialized.c:5: ... accessing uninitialized left-value. assert \initialized(&r);
uninitialized.c:13: ... accessing left-value that contains escaping addresses.
                assert !\dangling(&p);
```

By default, Eva emits an alarm as soon as a value that may be uninitialized or a dangling address is read, even if this value is not used in any computation.

However, it may be normal for some fields in a struct or union to contain such dangerous contents in some cases. Thus, Eva *never* emits an alarm for a copy from memory to memory of a struct or an union containing dangling addresses or uninitialized contents. This behavior is safe because Eva warns later, as soon as an unsafe value is used in a computation –either directly or after having been copied from another location.

This relaxed behavior on structs and unions can be extended to scalar variables with the option `-eva-warn-copy-indeterminate`. Specifying `-eva-warn-copy-indeterminate=-f` on the command-line will cause the analyzer to not emit alarms on copy operations occurring in function `f`. The syntax `-@all` can also be used to activate this behavior for all functions. In this mode, the copy operations for which alarms are not emitted are assignments from lvalues to lvalues (`lv1 = lv2;`), passing lvalues as arguments to functions (`f(lv1);`), and returning lvalues (`return lv1;`). An exception is made for lvalues passed as arguments to library functions: in this case, because the function's code is missing, there is no chance to catch the undefined access later; the analyzer emits an alarm at the point of the call.

Trap representations of _Bool values

By default, Eva emits an alarm whenever a trap representation might be read from an lvalue of type `_Bool`. According to the C99 standard, the `_Bool` type contains the values 0 and 1, but any other value might be a trap representation, that is, an object representation that does not represent a valid value of the type. Trap representations can be created through unions or pointer casts.

```
1
2 union u_bool { _Bool b; unsigned char c; } ub;
3 void main () {
4   ub.c = 42;
5   _Bool b = ub.b;
6 }
```

```
frama-c -eva invalid_bool.c
```

```
  [eva:alarm] invalid_bool.c:5: Warning:
    trap representation of a _Bool lvalue. assert ub.b == 0 \/ ub.b == 1;
```

The option `-no-warn-invalid-bool` can be used to disable alarms on `_Bool` trap representations, in which case they are handled as correct `_Bool` values.

Undefined pointer comparison alarms

Proof obligations can also be emitted for pointer comparisons whose results may vary from one compilation to another, such as `&a < &b` or `&x+2 != NULL`. These alarms do not necessarily correspond to run-time errors, but relying on an undefined behavior of the compiler is in general undesirable (although this one is rather benign for current compilation platforms).

Although these alarms may seem unimportant, they should still be checked, because Eva may reduce the propagated states accordingly to the emitted alarm. For instance, for the `&x+2 != NULL` comparison, after emitting the alarm that the quantity `&x+2` must be reliably comparable to 0, the analysis assumes that the result of the comparison is 1. The consequences are visible when analyzing the following example:

```
1 int x,y,*p;
2 main(){
3   p = &x;
4   while (p++ != &y);
5 }
```

Eva finds that this program does not terminate. This seems incorrect because an actual execution will terminate on most architectures. However, Eva's conclusion is conditioned by an alarm emitted for the pointer comparison.

Eva only allows pointer comparisons that give reproducible results — that is, the possibility of obtaining an unspecified result for a pointer comparison is considered as an unwanted error, and is excluded by the emission of an alarm.

The analyzer can be instructed to propagate past these undefined pointer comparisons with option `-eva-undefined-pointer-comparison-propagate-all`. With this option, in the example program above, the values `0` and `1` are considered as results for the condition as soon as `p` becomes an invalid address. Therefore, Eva does not predict that the program does not terminate.

Conversely, verifications for undefined pointer comparisons can be deactivated using option `-eva-warn-undefined-pointer-comparison`. The possible settings are:

- `none`: never emit a pointer comparison alarm;
- `pointer`: emit an alarm only when the arguments of the comparison have pointer type;
- `all`: emit an alarm in all cases, including when comparing scalars that the analysis has inferred as possibly containing pointers.

Undefined side-effects in expressions

The C language allows compact notations for modifying a variable that is being accessed (for instance, `y = x++;`). The effect of these pre- or post-increment (or decrement) operators is undefined when the variable is accessed elsewhere in the same statement. For instance, `y = x + x++;` is undefined: the code generated by the compiler may have any effect, and especially not the effect expected by the programmer.

Sometimes, it is not obvious whether the increment operation is defined. In the example `y = *p + x++;`, the post-increment is defined as long as `*p` does not have any bits in common with `x`.

```
1  int x, y, z, t, *p, *q;
2  void main(int c)
3  {
4    if (c&1)
5      y = x + x++;
6    p = c&2 ? &x : &t;
7    y = *p + x++;
8    q = c&4 ? &z : &t;
9    y = *q + x++;
10 }
```

```
frama-c -eva se.c -unspecified-access
```

With option `-unspecified-access`, three warnings are emitted during parsing. Each of these only mean that an expression with side-effects will require checking after the Abstract Syntax Tree has been elaborated. For instance, the first of these warnings is:

```
[kernel] se.c:5: Warning: Unspecified sequence with side effect:
                 /*  <-  */
                 tmp = x;
                 /* x <- */
                 x ++;
                 /* y <- x tmp */
                 y = x + tmp;
```

Then Eva is run on the program. In the example at hand, the analysis finds problems at lines 5 and 7.

```
[eva:alarm] se.c:5: Warning: undefined multiple accesses in expression.
  assert \separated(&x, &x);
[eva:alarm] se.c:7: Warning: undefined multiple accesses in expression.
  assert \separated(&x, p);
```

At line 5, it can guarantee that an undefined behavior exists, and the analysis is halted. For line 7, it is not able to guarantee that `p` does not point to `x`, so it emits a proof obligation. Since it cannot guarantee that `p` always points to `x` either, the analysis continues. Finally, it does not warn for line 9, because it is able to determine that `*q` is `z` or `t`, and that the expression `*q + x++` is well defined.

Another example of statement which deserves an alarm is `y = f() + g();`. For this statement, it is unspecified which function will be called first. If one of them modifies global variables that are read by the other, different results can be obtained depending on factors outside the programmer's control. At this time, Eva does not check if these circumstances occur, and silently chooses an order for calling `f` and `g`. The statement `y = f() + x++;` does not emit any warning either, although it would be desirable to do so if `f` reads or writes into variable `x`. These limitations will be addressed in a future version.

Partially overlapping lvalue assignment

Vaguely related to, but different from, undefined side-effects in expressions, Eva warns about the following program:

```
1  struct S { int a; int b; int c; };
2
3  struct T { int p; struct S s; };
4
5  union U { struct S s; struct T t; } u;
6
7  void copy(struct S *p, struct S *q)
8  {
9    *p = *q;
10 }
11
12 int main(int c, char **v){
13   u.s.b = 1;
14   copy(&u.t.s, &u.s);
15   return u.t.s.a + u.t.s.b + u.t.s.c;
16 }
```

The programmer thought implementation-defined behavior was invoked in the above program, using an union to type-pun between structs S and T. Unfortunately, this program returns 1 when compiled with `clang -m32`; it returns 2 when compiled with `clang -m32 -O2`, and it returns 0 when compiled with `gcc -m32`.

For a program as simple as the above, all these compilers are supposed to implement the same implementation-defined choices. Which compiler, if we may ask such a rhetorical question, is right? They all are, because the program is undefined. When function `copy()` is called from `main()`, the assignment `*p = *q;` breaks C99's 6.5.16.1:3 rule. This rule states that in an assignment from lvalue to lvalue, the left and right lvalues must overlap either exactly or not at all.

The program breaking this rule means compilers neither have to emit warnings (none of the above did) nor produce code that does what the programmer intended, whatever that was. Launched on the above program, Eva says:

```
partially overlapping lvalue assignment. assert p == q || \separated(p, q);
```

By choice, Eva does not emit alarms for overlapping assignments of size less than `int`, for which reading and writing are deemed atomic operations. Finding the exact cut-off point for these warnings would require choosing a specific compiler and looking at the assembly it generates for a large number of C constructs. Contact us if you need such fine-tuning of the analyzer for a specific target platform and compiler.

Invalid function pointer access

When Eva encounters a statement of the form `(*e)(x);` and is unable to guarantee that expression `e` evaluates to a valid function address, an alarm is emitted. This includes invalid pointers (such as `NULL`), or pointers to a function with an incompatible type. In the latter case, an alarm is emitted, but Eva may nevertheless proceed with the analysis if it can give some meaning to the call. This is meant to account for frequent misconceptions on type compatibility (e.g. `void *` and `int *` are *not* compatible).

```
1  extern void * f1();
2  extern void f2(int);
3
4  void main(int c) {
5    int * (*p)(int);
6    void *x, *y;
7
8    p = &f1;
9    x = (*p)(c); // Alarm, but the analysis proceeds
10
11   p = &f2;
12   y = (*p)(c); // Call deemed entirely invalid
13 }
```

```
[eva:alarm] valid_function.c:9: Warning:
  pointer to function with incompatible type. assert \valid_function(p);
[kernel:annot:missing-spec] valid_function.c:9: Warning:
  Neither code nor specification for function f1, generating default assigns
  from the prototype
[eva] using specification for function f1
[eva:alarm] valid_function.c:12: Warning:
  pointer to function with incompatible type. assert \valid_function(p);
[eva] valid_function.c:12:
  assertion 'Eva,function_pointer' got final status invalid.
```

3.3 Log messages emitted by Eva

This section categorizes the non-alarms related messages displayed by Eva in `frama-c`, the batch version of the analyzer. When using `frama-c-gui` (the graphical interface), the messages are directed to different panels in the bottom right of the main window for easier access.

3.3.1 Results

With the batch version of Frama-C, all computation results, messages and warnings are displayed on the standard output. However, a compromise regarding verbosity had to be reached. Although variation domains for variables are available for any point in the execution of the analyzed application, the batch version only displays, for each function, the values that hold whenever the end of this function is reached.

3.3.2 Informational messages regarding propagation

Some messages warn that the analysis is making an operation likely to cause loss of precision. Other messages warn the user that unusual circumstances have been encountered by Eva.

In both these cases, the messages are not proof obligations and it is not mandatory for the user to act on them. They can be distinguished from proof obligations by the fact that they do **not** use the word "assert". These messages are intended to help the user trace the results of the analysis, and give as much information as possible in order to help them find when and why the analysis becomes imprecise. These messages are only useful when it is important to analyze the application with precision. Eva remains correct even when it is imprecise.

Examples of messages that result from the apparition of imprecision in the analysis are:

```
[eva] origin.c:14:
  Assigning imprecise value to pa1.
  The imprecision originates from Arithmetic {origin.c:14}

[eva] origin.c:15:
  writing somewhere in {ta1} because of Arithmetic {origin.c:14}.
```

Examples of messages that correspond to unusual circumstances are:

```
[kernel] alloc.c:20: Warning:
  all target addresses were invalid. This path is assumed to be dead.

[eva:locals-escaping] origin.i:86: Warning:
  locals {x} escaping the scope of local_escape_1 through esc2
```

Note that a few messages are prefixed with `[kernel]` instead of `[eva]`, for technical reasons, but it is the analysis by Eva which causes them to be emitted.

3.3.3 Analysis summary

At the end of the analysis, Eva produces a summary such as the following:

```
[eva:summary] ====== ANALYSIS SUMMARY ======
  ------------------------------------------------------------------------------
  6 functions analyzed (out of 44): 13% coverage.
  In these functions, 588 statements reached (out of 626): 93% coverage.
  ------------------------------------------------------------------------------
  No errors or warnings raised during the analysis.
  ------------------------------------------------------------------------------
  143 alarms generated by the analysis:
      71 integer overflows
      64 accesses to uninitialized left-values
       8 illegal conversions from floating-point to integer
  ------------------------------------------------------------------------------
  Evaluation of the logical properties reached by the analysis:
    Assertions      0 valid    0 unknown    0 invalid     0 total
    Preconditions  11 valid    0 unknown    0 invalid    11 total
  100% of the logical properties reached have been proven.
  ------------------------------------------------------------------------------
```

It contains:

- semantic coverage metrics, with the number of functions and statements analyzed;
- total number of errors and warnings, pointing out potential issues that could jeopardize the correction of the analysis;

- total number of alarms emitted by the analysis, grouped by kind;
- total number of logical properties (assertions and preconditions at each call-site) proven by the analysis. Note that this only indicates the logical statuses evaluated by Eva; some logical properties may have been proven by other plugins.

The summary provides a quick glance at the analysis, being especially useful for side-by-side comparisons of different parametrizations. It also allows one to quickly determine whether there remain issues to be resolved. More detailed information is provided through the graphical interface and by the Report plugin.

The summary display can be disabled by using option `-eva-msg-key=-summary`.

3.3.4 Audit messages (*experimental*)

Using options `-audit-prepare` and `-audit-check`, the user can produce and check some information relevant for auditing purposes.

`-audit-prepare <file>` outputs the following information:

- the list of all source files used during parsing: not only those given in the command line, but also those in #include directives, recursively. This usually includes Frama-C's standard library. For each file, its MD5 checksum is also printed;
- the list of *enabled* and *disabled* warning categories, for the kernel as well as for Eva. Warning categories are considered disabled when set to one of the following actions: *inactive*, *feedback*, and *feedback-once*. All other actions are considered as enabled;
- the list of Eva's *correctness parameters*, along with their values at the moment when Eva is run.

The information is written to `<file>`, in JSON format, unless it is the special value `-` (given as `-audit-prepare=-`), in which case the information is printed to the standard output in text format.

The complementary option `-audit-check file` takes a JSON file produced by `-audit-prepare` and checks if all checksums, warning category statuses and correctness parameters match. Any discrepancies are reported and result in an error by default.

The main intent of these options is to help users perform audit-related tasks concerning an analysis performed with Eva. It also helps fine-tuning analyses without affecting its correctness; for instance, since it omits information related to parameters which do not affect correctness, the user is free to adjust them to improve the speed and precision of the analysis.

Note that these options are still in experimental stage, and should not be blindly relied upon for strict auditing purposes. For instance, they do not record information related to syntactic transformations performed by plugins such as Variadic, which can have an indirect impact on its correctness.

Please contact the Frama-C development team if you intend to use these options in a production setting.

3.4 About these alarms the user is supposed to check...

When writing a Frama-C plug-in to assist in reverse-engineering source code, it does not really make sense to expect the user to check the alarms that are emitted by Eva. Consider for instance Frama-C's slicing plug-in. This plug-in produces a simplified version of a program. It is often applied to large unfamiliar codebases; if the user is at the point where they need a slicer to make sense of the codebase, it's probably a bad time to require them to check alarms on the original unsliced version.

The slicer and other code comprehension plug-ins work around this problem by defining the results they provide as "valid for well-defined executions". In the case of the slicer, this is really the only definition that makes sense. Consider the following code snippet:

```
1  x = a;
2  y = *p;
3  x = x+1;
4  // slice for the value of x here.
```

This piece of program is begging for its second line to be removed, but if `p` can be the `NULL` pointer, the sliced program behaves differently from the original: the original program exits abruptly on most architectures, whereas the sliced version computes the value of `x`.

It is fine to ignore alarms in this context, but the user of a code comprehension plug-in based on Eva should study the categorization of alarms in section 3.2 with particular care. Because Eva is more aggressive in trying to extract precise information from the program than other analyzers, the user is more likely to observe incorrect results if there is a misunderstanding between him and the tool about what assumptions should be made.

Everybody agrees that accessing an invalid pointer is an unwanted behavior, but what about comparing two pointers with `<=` in an undefined manner or assuming that a signed overflow wraps around in 2's complement representation? Function `memmove`, for instance, typically does the former when applied to two addresses with different bases. Yet, currently, if there appears to be an undefined pointer comparison, Eva propagates a state that may contain only "optimistic" (assuming the undefined circumstances do not occur) results for the comparison result and for the pointers.[1]

It is possible to take advantage of Eva for program comprehension, and all existing program comprehension tools need to make assumptions about undefined behaviors. Most tools do not tell whether they had to make assumptions or not. Eva does: each alarm, in general, is also an assumption. Still, as implementation progresses and Eva becomes able to extract more information from the alarms it emits, one or several options to configure it either not to emit some alarms, or not to make the corresponding assumptions, will certainly become necessary. This is a consequence of the nature of the C language, very partially defined by a standard that also tries to act as lowest common denominator of existing implementations, and at the same time used for low-level programming where strong hypotheses on the underlying architecture are needed.

3.5 API

Both the user (through the GUI) or a Frama-C plug-in can request the evaluation, at a specific statement, of an lvalue (or an arbitrary expression). The variation domain thus obtained

[1] As explained earlier, in this particular case, it is possible to get all possible behaviors using option `-eva-undefined-pointer-comparison-propagate-all`.

contains all the values that this lvalue or expression may have anytime an actual execution reaches the selected statement.

In fact, from the point view of Eva, the graphical interface that allows to observe the values of variables in the program is very much an ordinary Frama-C plug-in. It uses the same functions (registered in module `Db.Value`) as other plug-ins that interface with Eva. This API is not very well documented yet, but one early external plug-in author used the GUI to get a feeling of what Eva could provide, and then used the OCaml source code of the GUI as a reference for obtaining this information programmatically.

3.5.1 Eva API overview

The function `!Db.Value.access` is one of the functions provided to custom plug-ins. It takes a program point (of type `Cil_types.kinstr`), the representation of an lvalue (of type `Cil_types.lval`) and returns a representation of the possible values for the lvalue at the program point.

Another function, `!Db.Value.lval_to_loc`, translates the representation of an lvalue into a location (of type `Locations.location`), which is the analyzer's abstract representation for a place in memory. The location returned by this function is free of memory accesses or arithmetic. The provided program point is used for instantiating the values of variables that appear in expressions inside the lvalue (array indices, dereferenced expressions). Thanks to this and similar functions, a custom plug-in may reason entirely in terms of abstract locations, and completely avoid the problems of pointers and aliasing.

The Frama-C Plug-in Development Guide contains more information about developing a custom plug-in.

Chapter 4

Graphical interface (GUI)

This chapter presents some aspects of the graphical interface of Eva. More information can be found in the Frama-C blog, under the keyword `tutorial`. Some examples shown in this section are taken from the Monocypher tutorial, presented in the blog.

A caveat. As a general recommendation, **do not** start your analyses within the GUI. Use the command-line. You should consider Frama-C/Eva as a command-line tool with a viewer (the GUI). The Frama-C GUI is not an IDE (e.g. you cannot edit code with it), and Eva does not use the GUI for anything else other than rendering its results. It is recommended to run the value analysis using the command line, and then saving the result to a Frama-C save file (see Section 6.1).

4.1 A general view of the GUI

After running the value analysis and saving your results, it is a good time to check what the result looks like, using the GUI:

```
frama-c-gui -load value.sav
```

In the screenshot of Figure 4.1, we indicate some parts of the GUI that are useful when inspecting Eva results (besides the source view). We also indicate some parts that are never (or rarely) used with Eva.

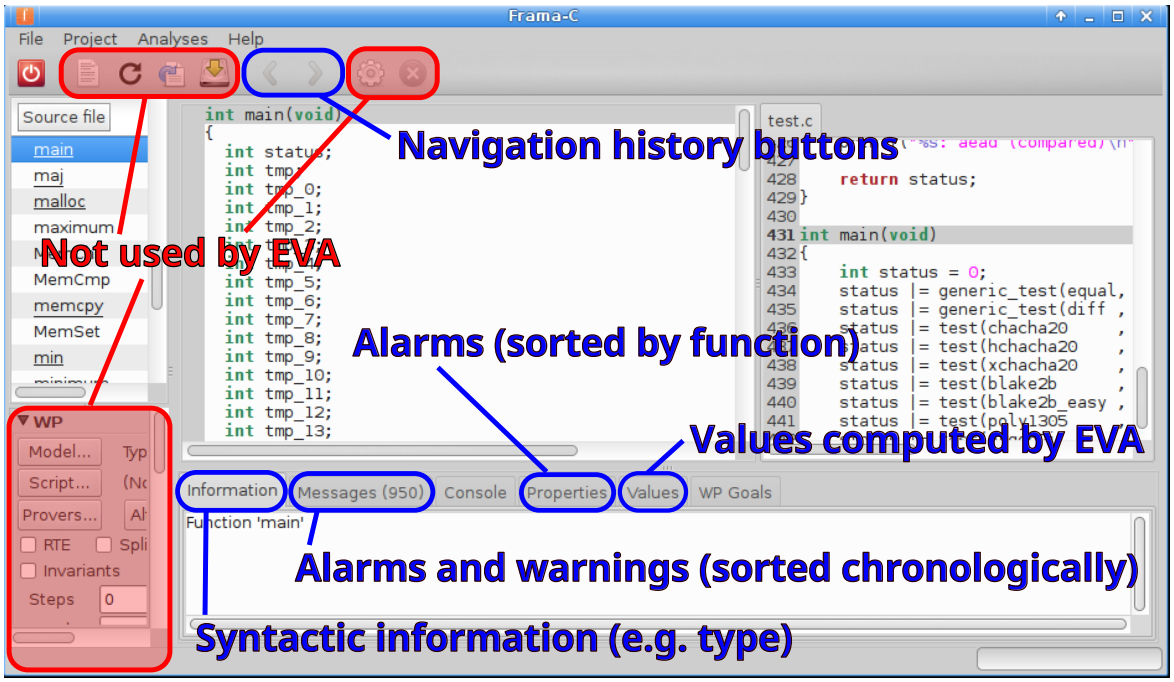


Figure 4.1: Frama-C GUI for Eva

Note that the Properties tab (between Console and Values) is not updated automatically: you need to click on the *Refresh* button before it outputs anything, and after changing filters.

Like many GUI-integrated plug-ins, Eva also has a side panel that is displayed below the globals list, on the lower left corner of the GUI. This panel can be folded/unfolded using the

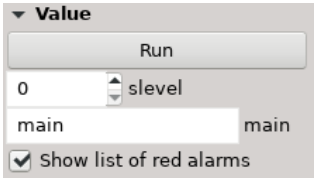


Figure 4.2: GUI side panel for Eva

arrow button on the left, and when unfolded (Figure 4.2) it displays some controls. The *Run* button runs (or re-runs) the analysis, using the specified slevel and with the specified main function. This is useful only for small examples and rarely used in practice. Also, notice that emitted warnings are persistent in the GUI, so even if a new run of the value analysis (e.g. with higher slevel) produces less alarms, the previous warnings will still be displayed in the *Messages* panel.

The checkbox *Show list of red alarms* shows or hides the *Red alarms* panel, described in Section 4.5.

4.2 Detecting and understanding non-termination

Assume that the log of your analysis contains the `NON TERMINATING FUNCTION` message for the `main` function. We know that at some point in the program we will have red statements in the GUI, which indicate unreachable code.

By scrolling down from the `main` function, we reach the non-terminating statement, which in our example is a call to `test_x25519` (Figure 4.3).

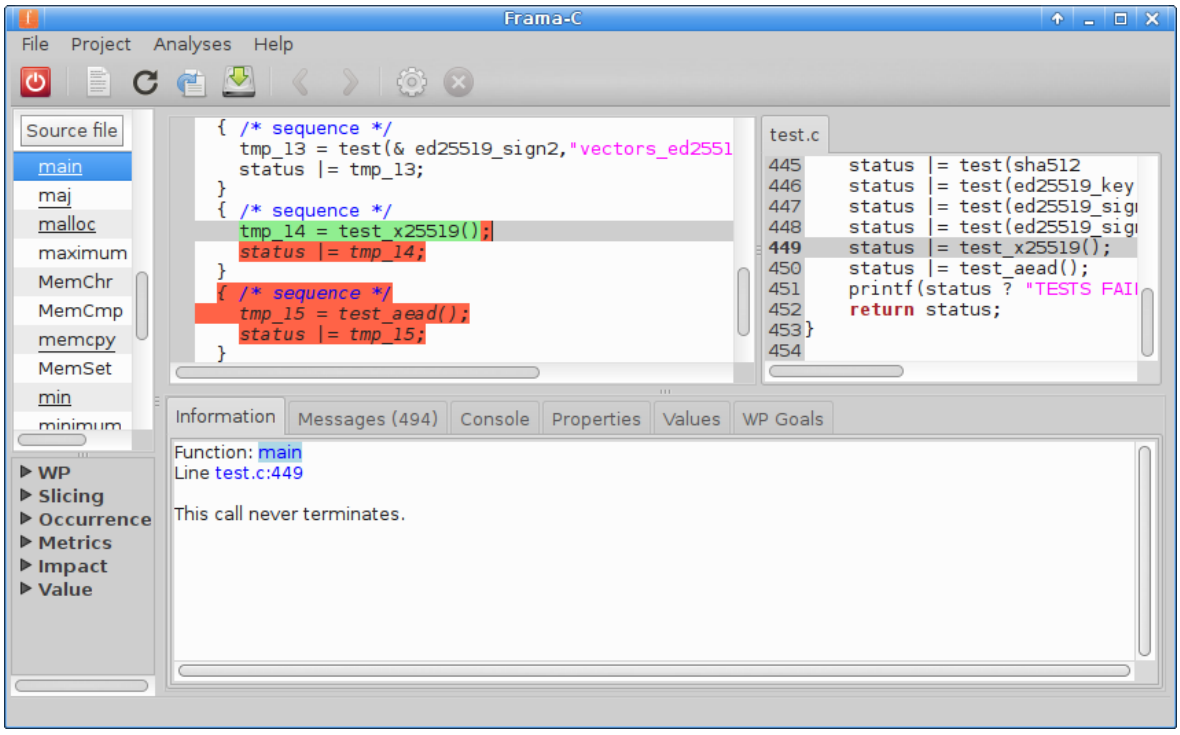


Figure 4.3: Unreachable code in the Frama-C GUI

Note the red semicolon at the end of the statement, and the fact that the statements that follow it are also red. If we click on the statement, the *Information* panel says that *This call never terminates.*

You can right-click on the function and *Go to the definition of* `test_x25519`, and you will find the same thing inside, this time a call to `crypto_x25519_public_key`, and so on, until you reach `fe_tobytes`, which is slightly different: it contains a `for` loop (defined via a macro `FOR`), after which all statements are red, but the loop itself is not an infinite loop: it simply iterates `i` from 0 to 5. How can this be non-terminating?

The answer, albeit non-intuitive, is simple: there is one statement inside the loop which is non-terminating, but *not* during the first iteration of the loop. Because the GUI colors are related to the consolidated result of all callstacks (i.e., if there is at least one path which reaches a statement, it is marked as reachable), it cannot show precisely which callstack led to the non-termination.

4.3 Values Panel

The Values panel, depicted in Figure 4.4, is arguably the most powerful inspection tool for the Eva plug-in in the Frama-C GUI.

The values displayed in this panel are related to the green highlighted zone in the Cil source. This zone can be a statement, an expression, an ACSL annotation, etc. Composite expressions can be selected by clicking on or near their operators. Each kind of selected expression has a set of associated context menus. For instance, an expression corresponding to a variable contains a *Go to definition* context menu when right-clicked on.

The Ctrl+E shortcut is equivalent to highlighting a statement, then right-clicking *Evaluate ACSL term.* This opens a dialog (Figure 4.5) where you can enter an arbitrary ACSL term. Its value will be evaluated in the current statement and displayed in the *Values* panel.

The Ctrl+Shift+E shortcut is slightly more powerful: it also evaluates *predicates*, such as `\valid(p)`. This command is not available from any menu.

The *Multiple selections* checkbox allows adding several expressions to be compared side-by-side. When checked, highlighting an expression in the same statement adds a column with its value. Note that highlighting a different statement results in resetting all columns.

The three checkboxes to the right are seldom used (their default values are fine most of the time): *Expand rows* simply expands all callstacks (but generates visual clutter); *Consolidated value* displays the row *all* (union of all callstacks); and *Per callstack* displays a row for each separate callstack.

The callstacks display has several contextual menus that can be accessed via right-clicks (Figure 4.6).

Let us start from the bottom: right-clicking on a callstack shows a popup menu that allows you to *focus* on a given callstack. This focus modifies the display in the Cil code viewer: reachability will only be displayed for the focused callstack(s). We will come back to that later.

Right-clicking on a cell containing a value allows filtering on all callstacks for which the expression has the same value. This is often used, for instance, to focus on all callstacks in which a predicate evaluates to *invalid* or *unknown.*

Finally, clicking on the column headers allows filtering columns.

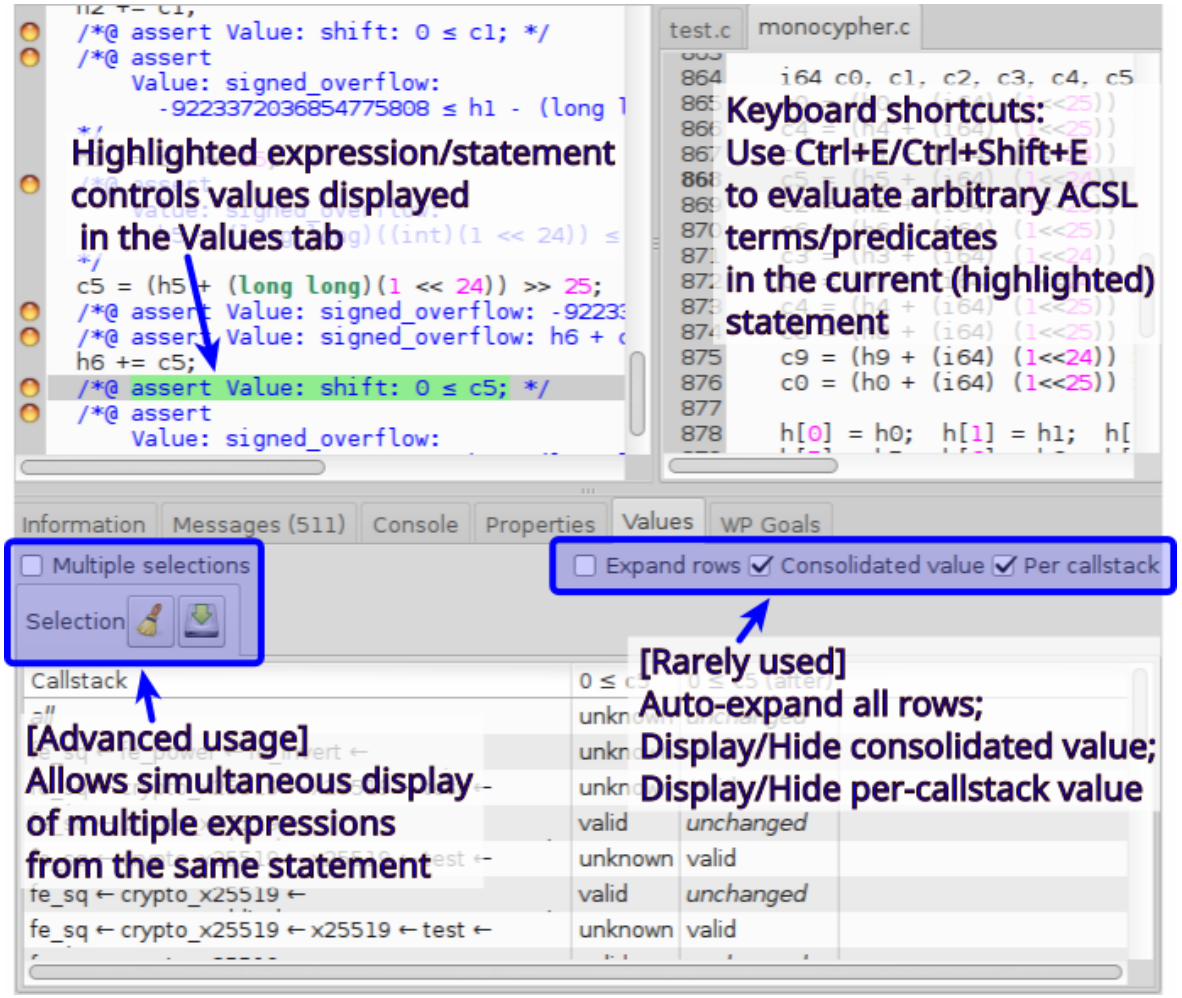


Figure 4.4: Values panel

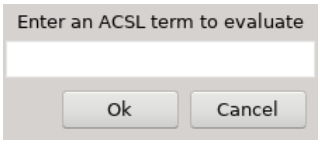


Figure 4.5: Evaluate ACSL term dialog, accessible via a context menu or by pressing Ctrl+E.

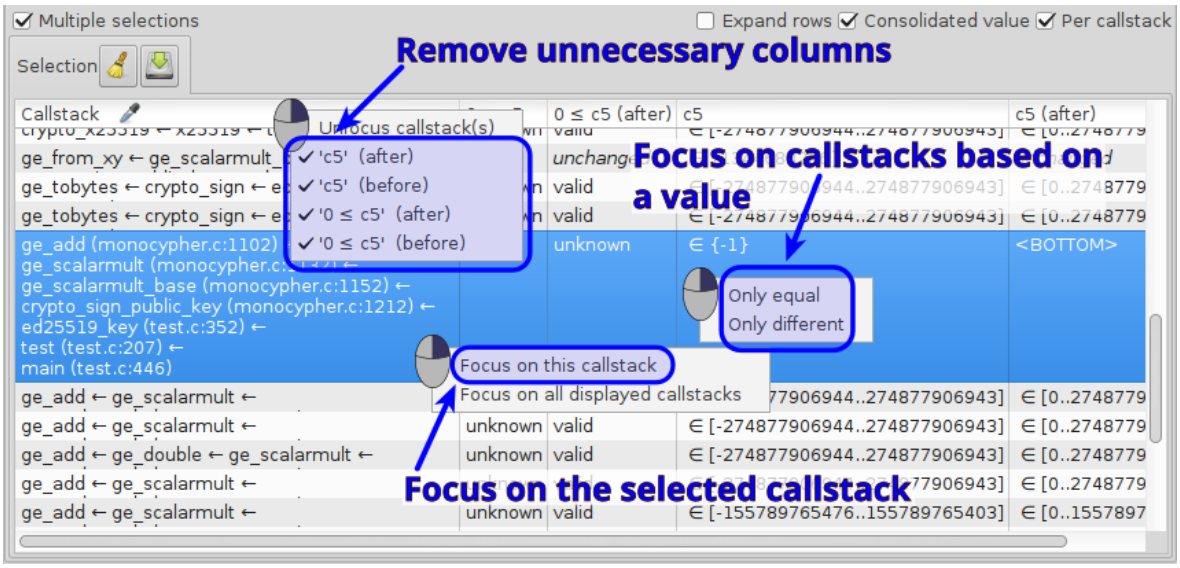


Figure 4.6: Callstacks display

Note that the Callstacks column header displays a pipette icon when a filter is being applied, to remind you that other callstacks exist.

4.3.1 Filtering non-terminating callstacks

In our code, despite the existence of 40 callstacks, only one of them is non-terminating. If you highlight the `0 ≤ c5` expression before statement `h5 -= c5 << 25`, you will see that only a single callstack displays *invalid* in the column `0 ≤ c5`. Focus on this callstack using the popup menu, then highlight expression `c5` in the Cil code. You will obtain the result displayed in Figure 4.7.

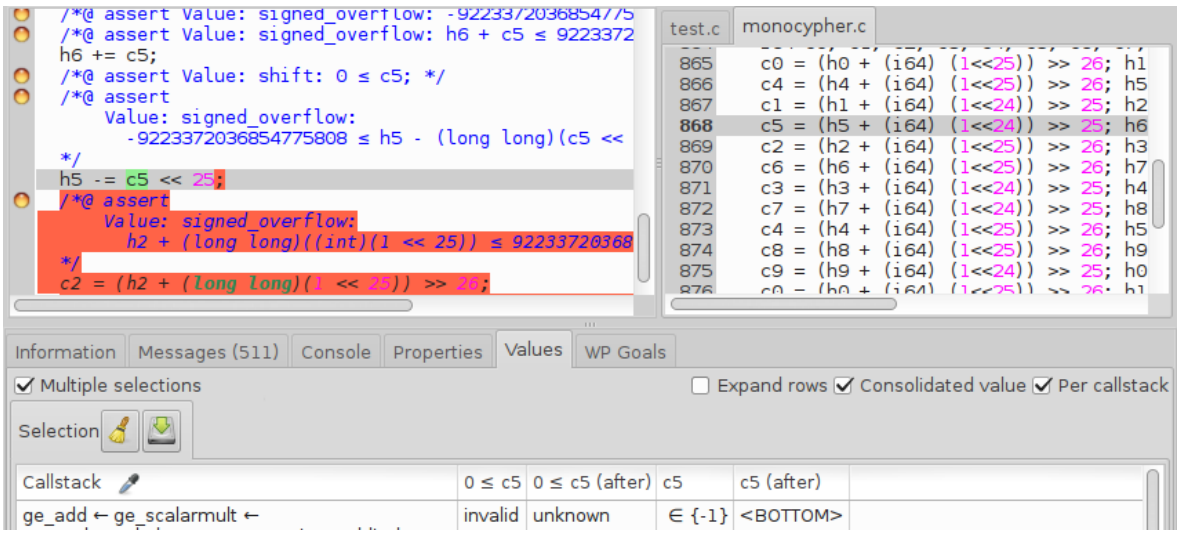


Figure 4.7: Focused on a non-terminating callstack

As you can see, the GUI now displays the statements following `h5 -= c5 << 25` in red, indicating thay they are unreachable in the currently focused callstacks. The exact value that caused this is shown in column `c5`: `-1`. The C standard considers the left-shift of a negative

number as undefined behavior. Because `-1` is the only possible value in this callstack, the reduction caused by the alarm leads to a post-state that is `<BOTTOM>`.

4.4 Finding origins of alarms and imprecisions via the Studia plug-in

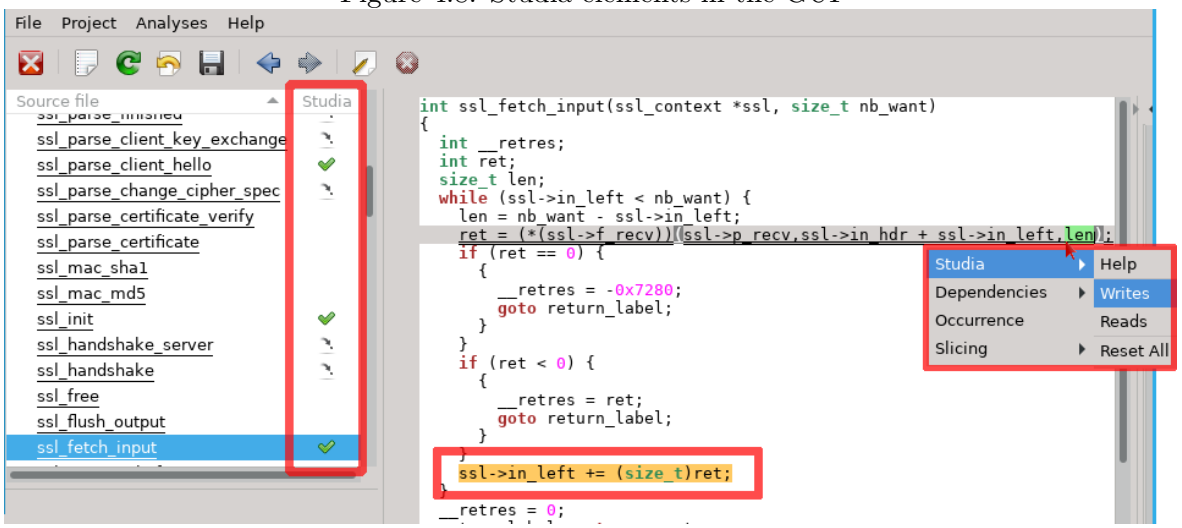
The Studia[1] plug-in is used to track the origins of values computed by Eva. For a given lvalue, it highlights all statements that may have written/read it.

Studia is invoked by right-clicking on a lvalue, selecting the *Studia* menu, then the *Writes* or *Reads* menu (see Figure 4.8). This will highlight all the instructions that may have defined (or read) the selected lvalue. *Studia* can also be used on arbitrary lvalues: when called through the right-click menu with no lvalue selected, *Studia* displays a dialog box in which an arbitrary lvalue can be typed.

When a lvalue is highlighted, a new column (*Studia*) appears on the file tree. It shows a check mark next to each function that directly writes/reads the highlighted lvalue, and an arrow next to each function that *indirectly* writes/reads the chosen value, that is, the callers of the functions marked with a check mark.

Each statement writing/reading the chosen value is highlighted in orange in the Cil code. Different shades of orange are used to distinguish between direct and indirect accesses.

Figure 4.8: Studia elements in the GUI



Typical usage of Studia consists in: starting the GUI, selecting an alarm (for instance, a possibly invalid memory access), inspecting the lvalue that causes the alarm (usually an imprecise value), then using Studia to find where the lvalue was defined. To find the root cause of a given loss of precision, it may be necessary to reiterate the process.

4.5 Detecting branches abandoned because of red alarms

When analyzing code, the value analysis sometimes encounters undefined behaviors so severe that the analysis cannot proceed afterwards. This is the case in the code fragment below:

[1]The name *Studia* is related to its applicability to case studies.

no state remains to be propagated after the addition, because the uninitialized access is guaranteed.

```
int x;
int y = x + 1;
```

This example is marked as non-terminating, both in the textual log and in the GUI. However, things are not always as clear-cut. Replace `x` by a pointer access, and imagine that only in *some* contexts the memory location is uninitialized.

```
void f(int *p) {
  if (rand ()) {
    int y = *p + 1;
  }
}

void main() {
  int x = 1, y;
  f(&x);
  f(&y);
}
```

In this example, all intructions "terminate" in the sense of Section 4.2. Yet, one branch is cut abruptly in the analysis of `f`.

Even more insidious is a loop where an operation fails only in the last iterations. In the example below, accessing `t[i]` with `i==10` is always invalid, but this is neither reflected in the Properties panel nor in the Values panel.

```
void main() {
  int i, t[10];
  for (i=0; i<10; i++) {
    t[i] = i;
  }
  int j = 0;
  for (i=0; i<=10; i++) {
    j += t[i];
    if (rand ()) break;
  }
}
```

The *Red alarms* panel (Figure 4.9) can be used to detect such kinds of severe alarms. The semantics it implements is the following: if in at least *one* analysis context, the alarm received an Invalid status (the ACSL property does not hold), then the alarm is present in the panel. Back to our second example, `\initialized (p)` is false. The *Nb contexts* column indicates in how many callstacks such an Invalid status was emitted during the analysis.

Information on non-terminating branches is also available through the *Values* panel (Figure 4.10). Once you have selected a property listed in the *Red alarms* panel, a new column appears, which displays red indicators. The way to read this information is: "in this context, the property evaluated to false at least once".

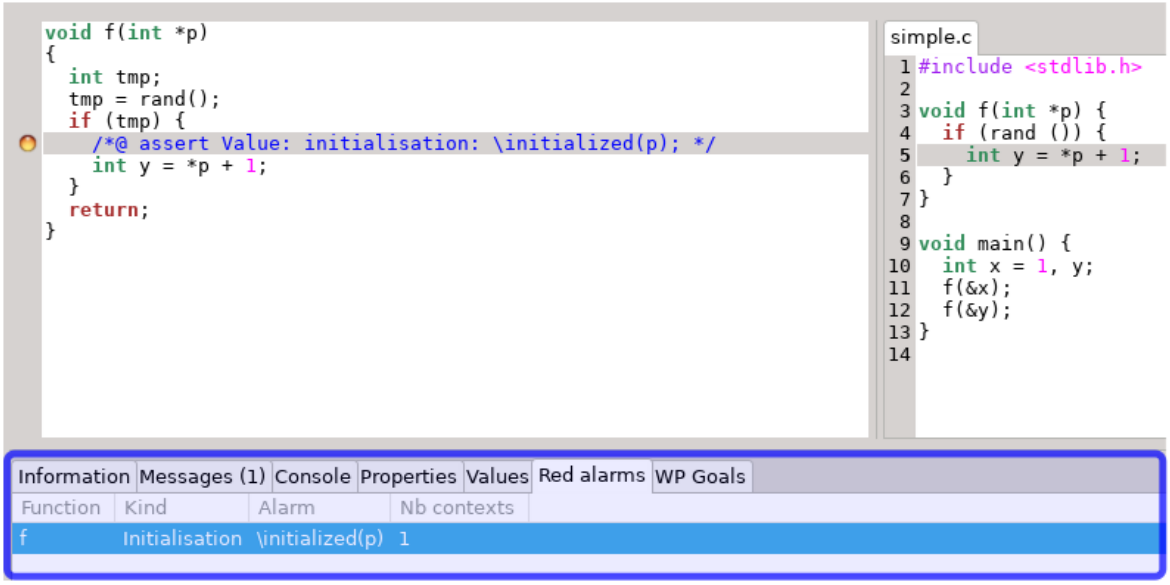


Figure 4.9: Red alarms panel

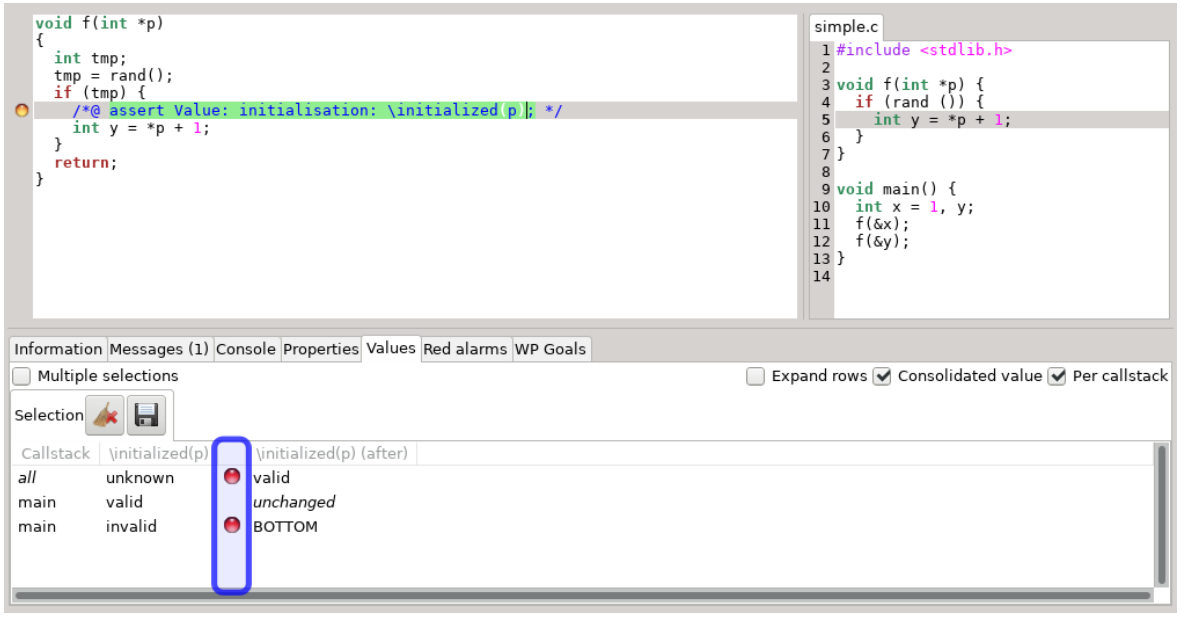


Figure 4.10: Indicators of red alarms in the Values panel

Chapter 5

Limitations and specificities

Nobody is perfect.

This chapter describes how the difficult constructs in the C language are handled in Eva. The constructs listed here are difficult for all static analyzers in general. Different static analysis techniques can often be positioned with respect to each other by looking only at how they handle loops, function calls and partial codebases.

Eva works best on embedded code or embedded-like code without multithreading, although it is usable (with modeling work from the user) on applications that include it. Dynamic allocation is supported in limited form, but imprecisions may accumulate quickly (e.g. linked lists often lead to suboptimal results).

5.1 Prospective features

Eva does not check all the properties that could be expected of it[1]. Support for each of these missing features could arrive if the need was expressed. Below are some of the existing limitations.

5.1.1 Strict aliasing rules

Eva does not check that the analyzed program uses pointer casts in a way that is compatible with strict aliasing rules. This is one of the major current issues of the C world because compilers only recently began to take advantage of these rules for optimization purposes. However, the issue has passed unnoticed for critical embedded code, because for various reasons including traceability, this code is compiled with most optimizations disabled.

[1] There are 245 unspecified or undefined behaviors in Annex J of the C99 standard.

5.1.2 Const attribute inside aggregate types

Some memory locations can be read from but not written to. An example of such a memory location is a constant string literal (`"foo"`). The ACSL specification language sports a predicate `\valid_read` to express that a memory location is valid for reading but does not have to be valid for writing. Accordingly, Eva emits alarms using `\valid_read(lv)` when an lvalue `lv` is read from, and `\valid(lv)` when `lv` is written to.

Variables with a const-qualified type are among the memory locations that Eva knows to be good to read from but forbidden to write to. However, the const type qualifier is currently only handled when placed at the top-level of the type of a global variable or formal argument. Other const locations are considered writable.

5.1.3 Alignment of memory accesses

Eva currently does not check that memory accesses are properly aligned in memory. It assumes that non-aligned accesses have only a small time penalty (instead of causing an exception) and that the programmer is aware of this penalty and is accessing (or seems to be accessing) memory in a misaligned way on purpose.

5.2 Loops

The analysis of a source program always takes a finite time. The fact that the source code contains loops, and that some of these loops do not terminate, can never induce the analyzer itself to loop forever. In order to guarantee this property, the analyzer may need to introduce approximations when analyzing a loop.

Let us assume, in the following lines, that the function `c` is unknown:

```
1  n=100;
2  i=0;
3  y=0;
4  do
5    {
6      i++;
7      if (c(i))
8        y = 2*i;
9    }
10 while (i<n);
```

The Eva plug-in could provide the best possible sets of values if the user explicitly instructed it to study step by step each of the hundred loop iterations. Without any such instruction, it analyses the body of the loop much less than one hundred times. It is able to provide the approximated, but correct, information that after the loop, `y` contains an even number between 0 and 256. This is an over-approximation of the most precise correct result, which is "an even number between 0 and 200". Section 6.4 introduces different ways for the user to influence the analyzer's strategy with respect to loops.

5.3 Functions

Without special instructions from the user, function calls are handled as if the body of the function had been expanded at the call site. In the following example, the body of `f` is analyzed again at each analysis of the body of the loop. The result of the analysis is as precise as the result obtained for the example in section 5.2.

```
1  int n, y;
2  void f(int x) { y = x; }
3
4  void main_1(void) {
5    int i;
6
7    n=100;
8    i=0;
9    y=0;
10   do
11     {
12       i++;
13       if (c(i))
14         f(2*i);
15     }
16   while (i<n);
17
18 }
```

Calls to variadic functions are handled by the Variadic plug-in, which translates calls to variadic functions into semantically-equivalent calls, either using arrays as arguments or via calls to specialized variants of the function. Such translations are enabled by default whenever the corresponding prototypes (e.g. `stdio.h` for `printf`) are included. Calls to variadic functions in the C standard library also include ACSL specifications, which Eva uses to interpret their behavior.

Recursive functions are partially supported by Eva: only a bounded number of recursive calls can be analyzed, and a user-written specification is required to interpret other calls. See section 6.3.9 for more details.

5.4 Analyzing a partial or a complete application

The default behavior of the Eva plug-in allows to analyze complete applications, that is, applications for which the source code is entirely available. In practice, it is sometimes desirable to limit the analysis to critical subparts of the application, by using other entry points than the actual one (the `main` function). Besides, the source code of some of the functions used by the application may not be available (library functions for instance). The plug-in can be used, usually with more work, in all these circumstances. The options for specifying the entry point of the analysis are detailed in this manual, section 6.3.10.

5.4.1 Entry point of a complete application

When the source code for the analyzed application is entirely available, the only additional information expected by the plug-in is the name of the function that the analysis should start from. Specifying the wrong entry point can lead to incorrect results. For instance, let us

assume that the actual entry point for the example of section 5.3 is not the function `main_1` but the following `main_main` function:

```
17 void main_main(void) {
18   f(15);
19   main_1();
20 }
```

If the user specifies the wrong entry point `main_1`, the plug-in will provide the same answer for variable `y` at the end of function `f` as in sections 5.2 and 5.3: the set of even numbers between 0 and 256. This set is not the expected answer if the actual entry point is the function `main_main`, because it does not contain the value 15.

The entry point of the analyzed application can be specified on the command line using the option `-main` (section 6.3.1). In the GUI, it is also possible to specify the name of the entry point at the time of launching Eva.

5.4.2 Entry point of an incomplete application

It is possible to analyze an application without starting from its actual entry point. This can be made necessary because the actual entry point is not available, for instance if the analysis is concerned with a library. It can also be a deliberate choice as part of a modular verification strategy. In this case, the option `-lib-entry`, described at section 6.3.3, should be used together with the option `-main` that sets the entry point of the analysis. In this mode, the plug-in does not assume that the global variables have kept their initial values (except for the variables with the const attribute).

5.4.3 Library functions

Another category of functions whose code may be missing is composed of the operating system primitives and functions from external libraries. These functions are called "library functions". The behavior of each library function can be specified through annotations (see chapter 8). The specification of a library function can in particular be provided in terms of modified variables, and of data dependencies between these variables and the inputs of the function (section 8.2). An alternative way to specify a library function is to write C code that models its behavior, so that its code is no longer missing from the point of view of the analyzer.

Frama-C provides a set of specifications for the most common functions in the C standard library and for some POSIX functions, plus a few extensions (BSD, GNU, etc.). These specifications allow the analysis of applications which use these libraries, but they become part of the *trusted computing base*: it is the responsibility of the user to verify that these specifications are correct with respect to the actual standard library implementation from the actual execution environment.

5.4.4 Choosing between complete and partial application mode

This section uses a small example to illustrate the pitfalls that should be considered when using Eva with an incomplete part of an application. This example is simplified but quite typical. This is the pattern followed by the complete application:

```
1 int ok1;
2
```

```
3  void init1(void) {
4    ...
5    if (error condition)
6      error_handling1();
7    else
8      ok1 = 1;
9  }
10
11 void init2(void) {
12   if (ok1) { ... }
13 }
14
15 void main(void) {
16   init1();
17   init2();
18   ...
19 }
```

If `init2` is analyzed as the entry point of a complete application, or if the function `init1` is accidentally omitted, then at the time of analyzing `init2`, Eva will have no reason to believe that the global variable `ok1` has not kept its initial value 0. The analysis of `init2` consists of determining that the value of the `if` condition is always false, and to ignore all the code that follows. Any possible run-time error in this function will therefore be missed by the analyzer. However, as long as the user is aware of these pitfalls, the analysis of incomplete sources can provide useful results. In this example, one way to analyze the function `init2` is to use the option `-lib-entry` described in section 6.3.3.

It is also possible to use annotations to describe the state in which the analysis should be started as a precondition for the entry point function. The syntax and usage of preconditions is described in section 8.1. The user should pay attention to the intrinsic limitations in the way Eva interprets these properties (section 8.1.2). A simpler alternative for specifying an initial state is to build it using the non-deterministic primitives described in section 9.2.1.

Despite these limitations, when the specifications the user wishes to provide are simple enough to be interpreted by the plug-in, it becomes possible and useful to divide the application into several parts, and to study each part separately (by taking each part as an entry point, with the appropriate initial state). The division of the application into parts may follow the phases in the application's behavior (initialization followed by the permanent phase) or break it down into elementary sub-pieces, the same way unit tests do.

5.4.5 Applications relying on software interrupts

The current version of the Eva plug-in is not able to take into account interrupts (auxiliary function that can be executed at any time during the main computation). As things stand, the plug-in may give answers that do not reflect reality if interrupts play a role in the behavior of the analyzed application. There is preliminary support for using Eva in this context in the form of support for `volatile` variables.

Unlike normal variables, the analyzer does not assume that the value read from a `volatile` variable is identical to the last value written there. Instead, a volatile variable in which only scalar values have been written is assumed to contain `[--..--]` when it is read from, regardless of the precise value of the contents that were previously written. The values of volatile pointers (*i.e* variables containing pointers and with volatile specifier) are an imprecise form of the address that has previously been assigned to the pointer. Finally, the handling of

(non-volatile) pointers to volatile locations is not finalized yet: it is not clear how the various complicated situations that can arise in this case should be handled. For instance, pointers to volatile locations may be pointing to locations that also have non-volatile access paths to them.

5.5 Conventions not specified by the ISO standard

Eva can provide useful information even for low-level programs that rely on non-portable C construct and that depend on the size of the word and the endianness of the target architecture.

5.5.1 The C standard and its practice

There exists constructs of the C language which the ISO standard does not specify, but which are compiled in the same way by almost every compiler for almost every architecture. For some of these constructs, the Eva plug-in assumes a reasonable compiler and target architecture. This design choice makes it possible to obtain more information about the behavior of the program than would be possible using only what is strictly guaranteed by the standard.

This stance is paradoxical for an analysis tool whose purpose is to compute only correct approximations of program behaviors. Then notion of "correctness" is necessarily relative to a definition of the semantics of the analyzed language. And, for the C language, the ISO standard is the only available definition.

However, an experienced C programmer has a certain mental model of the working habits of the compiler. This model has been acquired by experience, common sense, knowledge of the underlying architectural constraints, and sometimes perusal of the generated assembly code. Finally, the Application Binary Interface may constrain the compiler into using representations that are not mandated by the C standard (and which the programmer should not, *a priori*, have counted on). Since most compilers make equivalent choices, this model does not vary much from one programmer to the other. The set of practices admitted by the majority of C programmers composes a kind of informal, and unwritten, standard. For each C language construct that is not completely specified by the standard, there may exist an alternative, "portable" version. The portable version could be considered safer if the programmer did not know exactly how the non-portable version will be translated by their compiler. But the portable version may produce a code which is significantly slower and/or bigger. In practice, the constraints imposed on embedded software often lead to choosing the non-portable version. This is why, as often as possible, Eva uses the same standard as the one used by programmers, the unwritten one. It is the experience gained on actual industrial software, during the development of early versions of Frama-C as well as during the development of other tools, that led to this choice.

The hypotheses discussed here have to do with the conversions between integers and pointers, pointer arithmetic, the representation of `enum` types and the relations between the addresses of the fields of a same `struct`. As a concrete example, Eva plug-in assumes two-complement representation, which the standard does not guarantee, and whose consequences can be seen when converting between signed and unsigned types or with signed arithmetic overflows. These parameters are all fixed with the `-machdep` option as described in section 6.3.6.

Often, the ISO standard does not provide enough guarantees to ensure that the behaviors of the compiler during the compilation of the auto-detection program and during the compilation

of the application are the same. It is the additional constraint that the compiler should conform to a fixed ABI that ensures the reproducibility of compilation choices.

5.6 Memory model – Bases separation

This section introduces the abstract representation of the memory Eva relies on. It is necessary to have at least a superficial idea of this representation in order to interact with the plug-in.

5.6.1 Base address

The memory model used by Eva relies on the classical notion of "base address". Each variable, be it local or global, defines one and only one base address.

For instance, the definitions

```
1 int x;
2 int t[12][12][12];
3 int *y;
```

define three base addresses, for `x`, `t`, and `y` respectively. The sub-arrays composing `t` share the same base address. The variable `y` defines a base address that corresponds to a memory location expected to contain an address. On the other hand, there is no base address for `*y`, even though dynamically, at a given time of the execution, it is possible to refer to the base address corresponding to the memory location pointed to by `y`.

5.6.2 Address

An address is represented as an offset (which is an integer) with respect to a base address. For instance, the addresses of the sub-arrays of the array `t` defined above are expressed as various offsets with respect to the same base address.

5.6.3 Bases separation

The strongest hypothesis that the plug-in relies on is about the representation of memory and can be expressed in this way: **it is possible to pass from one address to another through the addition of an offset, if and only if the two addresses share the same base address**.

This hypothesis is not true in the C language itself: addresses are represented with a finite number of bits, 32 for instance, and it is always possible to compute an offset to go from an address to a second one by considering them as integers and subtracting the first one from the second one. The plug-in generates all the alarms that ensure, if they are checked, that the analyzed code fits in this hypothesis. On the following example, it generates a proof obligation meaning that "the comparison on line 8 is safe only if `p` is a valid address or if the base address of `p` is the same as that of `&x`".

```
1 int x, y;
2 int *p = &y;
3
4 void main(int c) {
5   if (c)
```

```
6       x = 2;
7     else {
8       while (p != &x) p++;
9       *p = 3;
10      }
11  }
```

It is mandatory to check this proof obligation. When analyzing this example, the analysis infers that the loop never terminates (because `p` remains an offset version of the address of `y` and can never be equal to the address of `x`). It concludes that the only possible value for `x` at the end of function `main` is 2, but this answer is provided *proviso quod* the proof obligation is verified through other means. Some actual executions of this example could lead to a state where `x` contains 3 at the end of `main`: only the proof obligation generated by the plug-in and verified by the user allows to exclude these executions.

In practice, the hypothesis of base separation is unavoidable in order to analyze efficiently actual programs. For the programs that respect this hypothesis, the user should simply verify the generated proof obligations to ensure the correctness of the analysis. For the programs that voluntarily break this hypothesis, the plug-in produces proofs obligations that are impossible to lift: this kind of program cannot be analyzed with the Eva plug-in.

Here is an example of code that voluntarily breaks the base separation hypothesis. Below is the same function written in the way it should have been in order to be analyzable with Frama-C.

```
1   int x,y,z,t,u;
2
3   void init_non_analyzable(void)
4   {
5     int *p;
6     // initialize variables with 52
7     for (p = &x; p <= &u; p++)
8       *p = 52;
9   }
10
11  void init_analyzable(void)
12  {
13    x = y = z = t = u = 52;
14  }
```

5.6.4 Dynamic allocation

Dynamic allocation is modeled by creating new bases. Each call to `malloc`/`realloc`/`calloc` potentially creates a new base, depending on the *builtins* (described in section 9.1) used – possibly resulting in an unbounded number of such bases. Dynamically allocated bases behave mostly like statically allocated ones, except that they come in two flavors:

- *strong* bases, allocated once per call to the allocation function, which are precise but may cause the analysis to diverge if they are called inside a loop. **It is the responsibility of the user to ensure that strong bases are not allocated inside loops.**
- *weak* bases, allocated once per callstack, which may confound information from multiple calls to the allocation function, overapproximating their contents. This results in a less

precise analysis, but maintains soundness and ensures termination. This is the safe default approach for allocations which may be nested inside loops.

Details about how to create and use these bases are provided in section 9.1.1.

5.7 What Eva does not provide

Values that are valid even if something bad happens

Eva provides sets of possible values under the assumption that the alarms emitted during the analysis have been verified by the user (if necessary, using other techniques). If during an actual execution of the application, one of the assertions emitted by Eva is violated, values other than those predicted by Eva may happen. See also questions 2 and 3 in chapter 10.

Termination or reachability properties

Although Eva sometimes detects that a function does not terminate, it cannot be used to prove that a function terminates. Generally speaking, the fact that Eva provides non-empty sets of values for a specific statement in the application does not imply that this statement is reachable in a real execution. Currently, Eva is not designed to prove the termination of loops or similar liveness properties. For instance, the following program does not terminate:

```
1 int x, y = 50;
2 void main()
3 {
4   while (y<100)
5     y = y + (100 - y)/2;
6   x = y;
7 }
```

If this program is analyzed with the default options of Eva, the analysis finds that every time execution reaches the end of `main`, the value of `x` is ≥ 100. This does not mean that the function always terminates or even that it may sometimes terminate (it does neither). When Eva proposes an interval for `x` at a point P, it should always be interpreted as meaning that *if P is reached, then at that time* `x` *is in the proposed interval*, and not as implying that P is reached.

Propagation of the displayed states

The values available through the graphical and programmatic interfaces do not come from a single propagated state but from the union of several states that the analyzer may have propagated separately. As a consequence, it should not be assumed that the "state" displayed at a particular program point has been propagated. In the following example, Eva did not emit any alarm for the division at line 8. This means that the divisor was found never to be null during an actual execution starting from the entry point. The values displayed at the level of the comment should not be assumed to imply that `(x - y)` is never null for arbitrary values `x`$\in \{0;1\}$ and `y`$\in \{0;1\}$.

```
1 int x, y, z;
2 main(int c){
3   ...
4   ...
5 /* At this point Eva guarantees:
```

```
6     x IN {0; 1}
7     y IN {0; 1}; */
8   z = 10 / (x - y);
9 }
```

With the option `-eva-slevel` described in section 6.4.1, the lines leading up to this situation may for instance have been:

```
3   x = c ? 0 : 1;
4   y = x ? 0 : 1;
```

Identically, the final states displayed by the batch version of Frama-C for each function are an union of all the states that reached the end of the function when it was called during the analysis. It should not be assumed that the state displayed for the end of a function `f` is the state that was propagated back to a particular call point. The only guarantee is that the state that was propagated back to the call point is included in the one displayed for the end of the function.

The only way to be certain that Eva has propagated a specific state, and therefore guarantee the absence of run-time errors under the assumptions encoded in that state, is to build the intended state oneself, for instance with non-deterministic primitives (section 9.2.1). However, the intermediate results displayed in the GUI can and should be used for cross-checking that the state actually built looks like intended.

Chapter 6

Parameterizing the analysis

Eva is automatic but gives you a little bit of control. Just in case.

Parameterization of Eva involves two main kinds of options: *correctness options* and *performance tuning options*. The former require understanding of their meaning and of the extra hypotheses they entail; used incorrectly, they can lead to a wrong analysis. The latter control the tradeoff between the quality of the results and the resources taken by the analyzer to provide them (CPU time and memory usage). These options cannot be used wrongly, in the sense that they do not affect the correctness of the results. However, using them efficiently is essential for scalability of the analysis.

Section 6.1 presents the overall methodology recommended when using Eva, especially for realistic code bases. Section 6.2 presents the general usage options of Eva in the command-line. The options described in section 6.3 are correctness options, while the remaining sections (6.4, 6.5, 6.6 and 6.7) deal with performance tuning options. Section 6.8 presents a derived analysis to obtain information about non-termination.

6.1 Three-step approach

For realistic code bases, an analysis with Eva requires several steps which are better performed separately, for several reasons:

- errors are confined to each of the separate steps, instead of being mingled together;
- partial results can be saved and reused, avoiding unnecessary recomputations;
- it is clearer which options and changes affect which stages, leading to better understanding of the process.

The recommended approach can be summarized as follows:

- parsing sources: `frama-c <sources> -save parsed.sav`;
- running Eva: `frama-c -load parsed.sav -eva -save eva.sav`;
- viewing its results on the GUI: `frama-c-gui -load eva.sav`.

The commands and options are detailed in the next section.

6.2 Command line

The parameters that determine Frama-C's behavior can be set through the command line. There are two main variants of Frama-C, one based on the command line (`frama-c`), and one which launches a graphical interface (`frama-c-gui`). The options understood by the Eva plug-in are described in this chapter. All options of Eva work identically for both the graphical interface and for the command line.

The options documented in this manual can be listed, with short descriptions, from the command line. Option `-kernel-help` lists options that affect all plug-ins. Option `-eva-help` lists options specific to the Eva plug-in. The options `-kernel-help` and `-eva-help` also list advanced options that are not documented in this manual.

Example:

```
frama-c -eva-help
```

```
...
-eva-slevel <n>   superpose up to <n> states when unrolling control flow.
                  The larger n, the more precise and expensive the analysis
                  (defaults to 0)
...
```

Historically, Eva was called Value, and most of its options were prefixed with `-val`*. All* `-val-*` *options are aliased to equivalent* `-eva-*` *functions; negative options of the form* `-no-val-*` *are aliased to* `-eva-no-*`*.*

6.2.1 Analyzed files and preprocessing

The analyzed files should be syntactically correct C. The files that do not use the `.i` extension are automatically pre-processed. The preprocessing command used by default is `gcc -C -E -I.`, but another preprocessor may be employed.

It is possible that files without a `.c` extension fail to pass this stage. It is notably the case with `gcc`, to which the option `-x c` should be passed in order to pre-process C files that do not have a `.c` extension.

Option `-cpp-extra-args <options>` allows giving additional options to the preprocessor, usually `-D` for defining macros and `-I` for including header directories.

In rare cases, you may need to use a different preprocessing command, via option `-cpp-command <cmd>`. If the patterns `%1` and `%2` do not appear in the text of the command, Frama-C invokes the preprocessor in the following way:

```
<cmd> -o <outputfile> <inputfile>
```

In the cases where it is not possible to invoke the preprocessor with this syntax, it is possible to use the patterns `%1` and `%2` in the command's text as place-holders for the input file (respectively, the output file). Here are some examples of use of this option:

```
frama-c-gui -eva -cpp-command 'gcc -C -E -I. -x c' file1.src file2.i
frama-c-gui -eva -cpp-command 'gcc -C -E -I. -o %2 %1' file1.c file2.i
frama-c-gui -eva -cpp-command 'copy %1 %2' file1.c file2.i
frama-c-gui -eva -cpp-command 'cat %1 > %2' file1.c file2.i
frama-c-gui -eva -cpp-command 'CL.exe /C /E %1 > %2' file1.c file2.i
```

6.2.2 Activating Eva

Option `-eva` activates Eva. Sets of values for the program's variables at the end of each analyzed function are displayed on standard output.

Many functionalities provided by Frama-C rely on Eva's results. Activating one of these automatically activates Eva, without it being necessary to provide the `-eva` option on the command-line. In this case, it should be kept in mind that all other options of Eva remain available for parameterization.

6.2.3 Saving the result of an analysis

The option `-save s` saves the state of the analyzer, after the requested computations have completed, in a file named `s`. The option `-load s` loads the state saved in file `s` back into memory for visualization or further computations.

Example :

```
frama-c -eva -deps -out -save result.sav file1.c file2.c
frama-c-gui -load result.sav
```

There is no specific extension for Frama-C saved files; the usual convention is to use `.sav`.

Most options are saved when `-save` *is used and do not need to be passed again when loading it. It is therefore useful to separate parsing options from analysis options, the former to be saved after parsing, the latter to be given after loading it.*

6.2.4 Controlling the output

By default, Eva emits all the alarms it finds (section 3.2) as both ACSL assertions and textual messages in the log. For big analyses, the log can become quite large. Since ACSL assertions are stored by the Frama-C kernel, and can be output using plugins such as Report, the textual output is partly redundant. Warning category[1] `alarm` allows to manage how these alarms are reported on the textual output. In particular, `-eva-warn-key alarm=inactive` will completely disable their output, and `-eva-warn-key alarm=feedback` will convert them into normal messages instead of warnings (equivalent to deprecated option `-eva-no-warn-on-alarms`[2]).

[1] See Frama-C User Manual [CCK+].

[2] Note that the use of `-eva-no-warn-on-alarms -eva-msg-key=-alarm` for completely deactivating the output will not work anymore, as `alarm` is not a debug category anymore.

6.3 Describing the analysis context

6.3.1 Specification of the entry point

The option `-main f` specifies that `f` should be used as the entry point for the analysis. If this option is not specified, the analyzer uses the function called `main` as the entry point.

6.3.2 Analysis of a complete application

By default (when the option `-lib-entry` is *not* set), the analysis starts from a state in which initialized global variables contain their initial values, and uninitialized ones contain zero. This only makes sense if the entry point (see section 6.3.1) is the actual starting point of this analyzed application. In the initial state, each formal argument of the entry point contains a non-deterministic value that corresponds to its type. Representative locations are generated for arguments with a pointer type, and the value of the pointer argument is the union of the address of this location and of `NULL`. For chain-linked structures, these locations are allocated only up to a fixed depth.

Example: for an application written for the POSIX interface, the prototype of `main` is:

```
int main(int argc, char **argv)
```

The types of arguments `argc` and `argv` translate into the following initial values:

```
argc ∈ [--..--]
argv ∈ {{ NULL ; &S_argv[0] }}
__retres ∈ UNINITIALIZED
S_argv[0] ∈ {{ NULL ; &S_0_S_argv[0] }}
      [1] ∈ {{ NULL ; &S_1_S_argv[0] }}
S_0_S_argv[0..1] ∈ [--..--]
S_1_S_argv[0..1] ∈ [--..--]
```

This is generally not what is wanted, but then again, embedded applications are generally not written against the POSIX interface. If the analyzed application expects command-line arguments, you should probably write an alternative entry point that creates the appropriate context before calling the actual entry point. That is, consider an example application whose source code looks like this:

```
int main(int argc, char **argv)
{
  if (argc != 2) usage();
  ...
}

void usage(void)
{
  printf("this application expects an argument between '0' and '9'\n");
  exit(1);
}
```

Based on the informal specification provided in `usage`, you should make use of the non-deterministic primitives described in section 9.2.1 to write an alternative entry point for the analysis like this:

```
int eva_main(void)
{
  char *argv[3];
  char arg[2];
  arg[0]=Frama_C_interval('0', '9');
  arg[1]=0;
  argv[0]="Analyzed application";
  argv[1]=arg;
  argv[2]=NULL;
  return main(2, argv);
}
```

For this particular example, the initial state that was automatically generated includes the desired one. This may however not always be the case. Even when it is the case, it is desirable to write an analysis entry point that positions the values of `argc` and `argv` to improve the relevance of the alarms emitted by Eva.

Although the above method is recommended for a complete application, it remains possible to let the analysis automatically produce values for the arguments of the entry point. In this case, the options described in section 6.3.4 below can be used to tweak the generation of these values to some extent.

6.3.3 Analysis of an incomplete application

The option `-lib-entry` specifies that the analyzer should not use the initial values for globals (except for those qualified with the keyword `const`). With this option, the analysis starts with an initial state where the numerical components of global variables (without the `const` qualifier) and arguments of the entry point are initialized with a non-deterministic value of their respective type.

Global variables of pointer type contain the non-deterministic superposition of `NULL` and of the addresses of locations allocated by the analyzer. The algorithm to generate those is the same as for formal arguments of the entry point (see previous section). The same options can be used to parameterize the generation of the pointed locations (see next section).

6.3.4 Tweaking the automatic generation of initial values

This sections describes the options that influence the automatic generation of initial values of variables. The concerned variables are the arguments of the entry point and, in `-lib-entry` mode, the non-const global variables.

Width of the generated tree

For a variable of a pointer type, there is no way for the analyzer to guess whether the pointer should be assumed to be pointing to a single element or to be pointing at the beginning of an array — or indeed, in the middle of an array, which would mean that it is legal to take negative offsets of this pointer.

By default, a pointer type is assumed to point at the beginning of an array of two elements. This number can be changed with option `-eva-context-width`.

Example: if the prototype for the entry point is `void main(int *t)`, the analyzer assumes `t` points to an array `int S_t[2]`.

For an array type, non-aliasing subtrees of values are generated for the first few cells of the array. All remaining cells are made to contain a non-deterministic superposition of the first ones. The number of initial cells for which non-aliasing subtrees are generated is also decided by the value of option `-eva-context-width`.

Example: with the default value 2 for option `-eva-context-width`, the declaration `int *(t[5]);` causes the following array to be allocated:

```
t ∈ {{ NULL ; &S_t[0] }}
S_t[0] ∈ {{ NULL ; &S_0_S_t[0] }}
   [1] ∈ {{ NULL ; &S_1_S_t[0] }}
   [2..4] ∈ {{ NULL ; &S_0_S_t[0] ; &S_1_S_t[0] }}
S_0_S_t[0..1] ∈ [--..--]
S_1_S_t[0..1] ∈ [--..--]
```

Note that for both arrays of pointers and pointers to pointers, using option `-eva-context-width 1` corresponds to a very strong assumption on the contents of the initial state with respect to aliasing. You should only use the argument `1` for option `-eva-context-width` in special cases, and use at least `2` for generic, relatively representative calling contexts.

Depth of the generated tree

For variables of a type pointer to pointers, the analyzer limits the depth up to which initial chained structures are generated. This is necessary for recursive types such as follows.

```
struct S { long v; struct S *next; };
```

This limit may also be observed for non-recursive types if they are deep enough.

Option `-eva-context-depth` allows to specify this limit. The default value is 2. This number is the depth at which additional variables named `S_...` are allocated, so two is plenty for most programs.

For instance, here is the initial state displayed by Eva in `-lib-entry` mode if a global variable `s` has type `struct S` defined above:

```
s.v ∈ [--..--]
 .next ∈ {{ NULL ; &S_next_s[0] }}
S_next_s[0].v ∈ [--..--]
       [0].next ∈ {{ NULL ; &S_next_0_S_next_s[0] }}
       [1].v ∈ [--..--]
       [1].next ∈ {{ NULL ; &S_next_1_S_next_s[0] }}
S_next_0_S_next_s[0].v ∈ [--..--]
                [0].next ∈ {{ NULL ; &S_next_0_S_next_0_S_next_s[0] }}
```

```
                          [0].next ∈
                          {{ garbled mix of &{
                              WELL_next_0_S_next_0_S_next_0_S_next_s}
                           (origin: Well) }}
                          [1].v ∈ [--..--]
```

In this case, if variable `s` is the only one which is automatically allocated, it makes sense to set the option `-eva-context-width` to one. The value of the option `-eva-context-depth` represents the length of the linked list which is modeled with precision. After this depth, an imprecise value (called a well) captures all the possible continuations in a compact but imprecise form.

Below are the initial contents for a variable `s` of type `struct S` with options `-eva-context-width 1 -eva-context-depth 1`:

```
s.v ∈ [--..--]
 .next ∈ {{ NULL ; &S_next_s[0] }}
S_next_s[0].v ∈ [--..--]
       [0].next ∈ {{ NULL ; &S_next_0_S_next_s[0] }}
S_next_0_S_next_s[0].v ∈ [--..--]
                [0].next ∈
                {{ garbled mix of &{WELL_next_0_S_next_0_S_next_s}
                 (origin: Well) }}
WELL_next_0_S_next_0_S_next_s[bits 0 to ..] ∈
                           {{ garbled mix of &{WELL_next_0_S_next_0_S_next_s}
                            (origin: Well) }}
```

The possibility of invalid pointers

In all the examples above, `NULL` was one of the possible values for all pointers, and the linked list that was modeled ended with a well that imprecisely captured all continuations for the list. Also, the `context-width` parameter for the generated memory areas has to be understood as controlling the maximum width for which the analyzer assumes the pointed area may be valid. However, in order to assume as little as possible on the calling context for the function, the analyzer also considers the possibility that any part of the pointed area might *not* be valid. Thus, by default, any attempt to access such an area results in an alarm signaling that the access may have been invalid.[3]

The option `-eva-context-valid-pointers` causes those pointers to be assumed to be valid (and `NULL` therefore to be omitted from the possible values) at depths that are less than the context width. It also causes the list to end with a `NULL` value instead of a well.

When analyzed with options `-eva-context-width 1 -eva-context-depth 1 -eva-context-valid-pointers`, a variable `s` of type `struct S` receives the following initial contents, modeling a chained list of length exactly 3:

```
s.v ∈ [--..--]
 .next ∈ {{ &S_next_s[0] }}
S_next_s[0].v ∈ [--..--]
       [0].next ∈ {{ &S_next_0_S_next_s[0] }}
S_next_0_S_next_s[0].v ∈ [--..--]
                [0].next ∈ {0}
```

6.3.5 State of the IEEE 754 environment

The IEEE 754 standard specifies a number of functioning modes for the hardware that computes floating-point operations. These modes determine which arithmetic exceptions can be produced and rounding direction for operations that are not exact.

By default, obtaining an infinite or NaN as result of a floating-point operation is treated as an unwanted error. Consequently, FPU modes related to arithmetic exceptions are irrelevant for the analysis. For non-default values of option `-warn-special-float`, the behavior of changing the floating-point environment is currently unspecified.

The compilation of, and the set of floating-point operations used, define roughly three categories of programs:

[3] For technical reasons, this also means that it is not possible to reduce the values of those areas through user-provided assertions (section 8.1.2).

1. The program uses only double and float floating-point types, does not change the default (nearest-even) floating-point rounding mode and is compiled with a compiler that neither generates `fmadd` instructions nor generates extended precision computations (historical x87 instruction set).
2. The compiler transforms floating-point computations as if floating-point addition or multiplication were associative, or transforms divisions into a multiplication by the inverse even when the inverse cannot be represented exactly as a floating-point number.
3. The program uses only double and float floating-point types, but either does not stay during the whole execution in the "nearest" floating-point rounding mode, or is compiled with a compiler that may silently insert `fmadd` instructions when only multiplications and additions appear in the source code, or are compiled for the x87 FPU.

Currently, only programs of the first category can be soundly analyzed by Eva.

6.3.6 Setting compilation parameters

Using one of the pre-configured target platforms

The option `-machdep` *platform* sets a number of parameters for the low-level description of the target platform, including the *endianness* of the target and size of each C type. The option `-machdep help` provides a list of currently supported platforms. The default is `x86_64`, an AMD64-compatible processor with what are roughly the default compilation choices of gcc.

Targeting a different platform

If your target platform is not listed, please contact the developers. An auto-detection program can be provided in order to check the hypotheses mentioned in section 5.5.1, as well as to detect the parameters of your platform. It comes under the form of a C program of a few lines, which should ideally be compiled with the same compiler as the one intended to compile the analyzed application. If this is not possible, the analysis can also be parameterized manually with the characteristics of the target architecture. The Frama-C Plugin Development Guide [SAC+15] contains a section about customizing the machine model.

6.3.7 Parameterizing the modeling of the C language

The following options are more accurately described as pertaining to Frama-C's modeling of the C language than as a description of the target platform, but of course the distinction is not always clear-cut. The important thing to remember is that these options, like the previous one, are dangerous options that should be used, or omitted, carefully.

Valid absolute addresses in memory

By default, Eva assumes that the absolute addresses in memory are all invalid. This assumption can be too restrictive, because in some cases there exist a limited number of absolute addresses which are intended to be accessed by the analyzed program, for instance in order to communicate with hardware.

The option `-absolute-valid-range m-M` specifies that the only valid absolute addresses (for reading or writing) are those comprised between `m` and `M` inclusive. This option currently allows to specify only a single interval, although it could be improved to allow several intervals in a future version.

Overflow in array accesses

Eva assumes that when an array access occurs in the analyzed program, the intention is that the accessed address should be inside the array. If it can not determine that this is the case, it emits an `out of bounds index` alarm. This leads to an alarm on the following example:

```
1 int t[10][10];
2
3 int main() {
4   return t[0][12];
5 }
```

Eva assumes that writing `t[0][...]`, the programmer intended the memory access to be inside `t[0]`. Consequently, it emits an alarm:

```
  accessing out of bounds index. assert 12 < 10;
```

The option `-unsafe-arrays` tells Eva to warn only if the address as computed using its modeling of pointer arithmetics is invalid. With the option, Eva does not warn about line 4 and assumes that the programmer was referring to the cell `t[1][2]`.

The default behavior is stricter than necessary but often produces more readable and useful alarms. To reiterate, in this default behavior Eva gets hints from the syntactic shape of the program. Even in the default mode, it does not warn for the following code.

```
4   int *p=&t[0][12];
5   return *p;
6 }
```

Option `-safe-arrays` also has an effect on the evaluation of the ACSL construct "`..`". When `t` is a known array, `t[..]` is strictly equivalent to `t[0..s-1]`, where `s` is the number of elements of `t`. Conversely, when option `-unsafe-arrays` is set, `t[..]` means `t[-∞..+∞]` – meaning that the location overlaps with neighbouring zones when `t` is inside an array or struct.

6.3.8 Dealing with library functions

When the Eva plug-in encounters a call to a library function, it may need to make assumptions about the effects of this call. The behavior of library functions can be described precisely by writing a contract for the function (chapter 8), especially using an `assigns` clause (section 8.2).

If no ACSL contract is provided for the function, the analysis uses the type of the function as its source of information for making informed assumptions. However, no guarantee is made that those assumptions over-approximate the real behavior of the function. The inferred contract should be verified carefully by the user.

6.3.9 Analyzing recursive functions

By default, recursive calls are not analyzed; instead, Eva uses the specification written by the user for the recursive function to interpret its recursive calls. The analysis of the function is then incomplete, as only its non-recursive calls are analyzed: values are inferred and alarms are emitted only for these calls. For the recursive calls, the analysis' soundness relies entirely on the specification provided by the user, which is not verified, and a warning is emitted.

```
[eva] file.c: Warning:
  Using specification of function <name> for recursive calls.
  Analysis of function <name> is thus incomplete and its soundness
  relies on the written specification.
```

If no ACSL contract is provided for the recursive function, a minimal specification is inferred by the Frama-C kernel from the function type, and an error is emitted. The specification is only generated to allow the analysis to continue past the recursive call, without any guarantees that it describes correctly the real behaviors of the function. In particular, only assigns clauses are created, without any preconditions. It is the user's responsibility to replace this generated specification by a correct one.

Unrolling recursive calls

Option `-eva-unroll-recursive-calls n` allows the precise analysis of recursive calls up to a depth of <n>. The function specification is only used when encountering a recursive call of depth greater than <n>.

On the example below, analyzed with `-eva-unroll-recursive-calls 10`:

- the first call `factorial(8)` is soundly and precisely analyzed without any warnings;
- the analysis of the second call `factorial(20)` is incomplete and produces a warning, as it resorts to the function specification for the tenth recursive call.

```
/*@ assigns \result \from i; */
int factorial (int i) {
  if (i <= 1) return 1;
  return i * factorial (i - 1);
}

void main(void) {
  int x = factorial(8);
  int y = factorial(20);
}
```

With option `-eva-unroll-recursive-calls`, the analysis of a recursive function can thus be complete and sound, when the number of recursive calls can be bounded by the analysis. In that case, no ACSL specification is required for the analysis of the recursive function.

However, even when the number of recursive calls is bounded in practice, the Eva analysis might be too imprecise to be complete.

```
/*@ assigns \result \from x; */
int mod3 (int x) {
  Frama_C_show_each(x);
  if ((x / 3) * 3 == x) return 0;
  else return 1 + mod3(x-1);
}

void main (int x) {
  int r = mod3(x);
}
```

The above example presents a recursive function `mod3`, which computes the congruence modulo 3 in up to three recursive calls. However, Eva is unable to perform a complete analysis of this function in the general case and will instead rely on the `mod3` specification, as it cannot reduce the new argument value of the recursive calls, as shown by the successive values printed by the `Frama_C_show_each` directive:

```
[eva] recursion-imprecise.c:3: Frama_C_show_each: [-2147483648..2147483646]
[eva] recursion-imprecise.c:3: Frama_C_show_each: [-2147483648..2147483644]
[eva] recursion-imprecise.c:3: Frama_C_show_each: [-2147483648..2147483643]
[eva] recursion-imprecise.c:5: Warning:
  Using specification of function mod3 for recursive calls of depth 4.
  Analysis of function mod3 is thus incomplete and its soundness
  relies on the written specification.
[eva] using specification for function mod3
```

Finally, note that the unrolling of a very large number of recursive calls can considerably slow down the analysis.

6.3.10 Using the specification of a function instead of its body

In some cases, one can estimate that the analysis of a given function `f` takes too much time. This can be caused by a very complex function, or because `f` is called many times during the analysis. Another situation is when a function already has a functional specification, proved for instance with the WP plug-in, and we do not want/need to analyze it with Eva.

In the cases above, a somewhat radical approach consists in replacing the entire body of the function by an ACSL contract that describes its behavior. See for example section 8.2 for how to specify which values the function reads and writes.

Alternatively, one can leave the body of the function untouched, but still write a contract. Then it is possible to use the option `-eva-use-spec f`. This instructs Eva to use the specification of `f` instead of its body each time a call to `f` is encountered. This is equivalent[4] to deleting the body of `f` for Eva, but not for the other plug-ins of Frama-C, that may study the body of `f` on their own.

Notice that option `-eva-use-spec f` loses some guarantees. In particular, the body of `f` is not studied at all by Eva. Neither are the functions that `f` calls, unless they are used by some other functions than `f`. Moreover, Eva does not attempt to check that `f` conforms to its specification. In particular, postconditions are marked as *unknown* with `-eva-use-spec`, while they are *considered valid* for functions without body. It is the responsibility of the user to verify those facts, for example by studying `f` on its own in a generic context.

6.4 Improving precision in loops

The default treatment of loops by the analyzer often produces results that are too approximate. Fine-tuning loops is one of the main ways to improve precision in the analysis.

When encountering a loop, the analyzer tries to compute a state that contains all the possible concrete states at run-time, including the initial concrete state just before entering the loop. This enclosing state, by construction, is often imprecise: typically, if the analyzed loop is initializing an array, the user does not expect to see the initial values of the array appear in the state computed by the analyzer. The solution in this case is to either unroll loops, using one of several available methods, or to add annotations (widening hints or loop invariants) that enable the analyzer to maintain precision while ensuring the analysis time remains bounded.

[4] Except for a few properties, as described in the next paragraph.

6.4.1 Loop unrolling

Whenever a loop has a fixed number of iterations (or a known upper bound), Eva can precisely analyze it by semantically unrolling each iteration, avoiding merging states from different iterations. This leads to increased cost in terms of analysis, but usually the cost increase is worth the improvement in precision.

Loop unrolling is often easy to apply, since it does not require much knowledge about the loop, other than an estimate of the number of iterations. If the estimate is too low, precision won't improve; if it is too high, it may lead to unnecessary work; but under no circumstances will it affect the correctness of the analysis.

Automatic loop unrolling

Eva includes a syntactic heuristic to automatically unroll simple loops whose number of iterations can be easily bounded. It is enabled via option `-eva-auto-loop-unroll <n>`, where `<n>` is the maximum number of iterations to unroll: loops with less than `<n>` iterations will be completely unrolled. If the analysis cannot infer that a loop terminates within less than `<n>` iterations, then no unrolling is performed.

`-eva-auto-loop-unroll` is recommended as the first approach towards loop unrolling, due to its low cost and ease of setup. An unrolling limit up to a few hundred seems suitable in most cases.

If *all* loops in a program need to be unrolled, one way to do it quickly consists in using option `-eva-min-loop-unroll <n>`, where `<n>` is the number of iterations to unroll in each loop. This option is very expensive, and its use should be limited.

For a more fine-grained analysis and for non-trivial loops, annotations are available to configure the loop unrolling on a case by case basis. These annotations take precedence over the automatic loop unrolling mechanism and can be combined with them, e.g. to automatically unroll *all but* a few loops.

With options `-eva-auto-loop-unroll AUTO -eva-min-loop-unroll MIN`:

- if a loop has a loop unroll annotation, it is unrolled accordingly;
- otherwise, if a loop has evidently less than `AUTO` iterations, it is completely unrolled;
- otherwise, the `MIN` first iterations of the loop are unrolled.

Loop unroll annotations

Individual loops can be unrolled by preceding them with a `loop unroll <n>` annotation, where `<n>` is the number of iterations to unroll. Such annotations must be placed just before the loop (i.e. before the `while`, `for` or `do` introducing the loop), and one annotation is required per loop, including nested ones. For instance:

```
#define NROWS 10
void main(void)
{
  int a[NROWS][20] = {0};
  //@ loop unroll NROWS;
  for (int i = 0; i < 10; i++) {
    //@ loop unroll (10+10);
    for (int j = 0; j < 20; j++) {
```

```
      a[i][j] += i + j;
    }
  }
}
```

The annotations above will ensure that Eva will unroll the loops and keep the analysis precise; otherwise, the array access `a[i][j]` might generate alarms due to imprecisions.

The `loop unroll` parameter can be any C expression evaluated to a single integer value by Eva each time the analysis reaches the loop. Otherwise, the annotation is ignored and a warning is issued. Constants obtained via #define macros, variables which always have a unique value and arithmetic operators are suitable. For expressions that have several possible values, the acceptability of the annotation depends on the precision of the analyzer. Note that there are interesting cases of non-constant expressions for unrolling annotations. The example below shows a function with two nested loops.

```
int t1[] = {1, 2, 3}, t2[] = {4, 5}, t3[] = {6, 7, 8, 9};
int *t[] = {t1, t2, t3};
int sizes[] = {3, 2, 4};
void main(void)
{
  int S = 0;
  //@ loop unroll 3;
  for (int i = 0 ; i < 3 ; i++) {
    //@ loop unroll sizes[i];
    for (int j = 0 ; j < sizes[i] ; j++) {
      S += t[i][j];
    }
  }
}
```

The number of iterations of the outer loop is constant while the number of iterations of the inner loop depends on the current iteration of the outer one. As we have instructed Eva to unroll the outer loop, it evaluates the parameter `sizes[i]` to a single possible integer for each iteration of the outer loop, and thus the inner loop annotation is accepted. In this example, it is also possible to use an upper bound like 4.

The unrolling mechanism is independent of `-eva-slevel` (see next subsection): annotated loops are always unrolled at least the specified number of times. If the loop has not been entirely unrolled, however, remaining `-eva-slevel` may be used to unroll more iterations.

While it is sometimes useful to unroll only the first iterations, the usual objective is full unrolling; for this reason, the user is informed whenever the specified unrolling value is insufficient to unroll the loop entirely:

```
void main()
{
  //@ loop unroll 20; // should be 21
  for (int i = 0 ; i <= 20 ; i ++) {
  }
}
```

```
[eva:loop-unroll:partial] loop-unroll-insuf.c:4: loop not completely unrolled
```

The message can be deactived via `-eva-warn-key loop-unroll=inactive`.

Note that using an unrolling parameter which is higher than the actual number of iterations of a loop doesn't generally have an effect on the analysis. The analyzer will usually detect that further iterations are not useful.

Loop annotations can also be used to prevent the automatic loop unrolling for some specific loops: adding `loop unroll 0` before a loop ensures that no iteration of the loop will be unrolled.

Unrolling via option *-eva-slevel*

The option `-eva-slevel n` indicates that the analyzer is allowed to separate, in each point of the analyzed code, up to `n` states from different execution paths before starting to compute the unions of said states. An effect of this option is that the states corresponding to the first, second,... iterations in a loop remain separated, as if the loop had been unrolled.

Unlike with `loop unroll` annotations, the number `n` to use with `-eva-slevel` depends on the nature of the control flow graph of the function to analyze. If the only control structure is a loop of `m` iterations, then `-eva-slevel m+1` allows to unroll the loop completely. The presence of other loops or of `if-then-else` constructs multiplies the number of paths a state may correspond to, and thus the number of states it is necessary to keep separated in order to unroll a loop completely. For instance, the nested simple loops in the following example require the option `-eva-slevel 55` in order to be completely unrolled:

```
1  int i,j,t[5][10];
2
3  void main(void)
4  {
5    for (i=0;i<5;i++)
6      for (j=0;j<10;j++)
7        t[i][j]=1;
8  }
```

When the loops are sufficiently unrolled, the result obtained for the contents of array `t` are the optimally precise:

```
t[0..4][0..9] ∈ {1}
```

The number to pass the option `-eva-slevel` is of the magnitude of the number of values for `i` (the 6 integers between 0 and 5) times the number of possible values for `j` (the 11 integers comprised between 0 and 10). If a value much lower than this is passed, the result of the initialization of array `t` will only be precise for the first cells. The option `-eva-slevel 28` gives for instance the following result for array `t`:

```
t{[0..1][0..9]; [2][0..5]} ∈ {1}
 {[2][6..9]; [3..4][0..9]} ∈ {0; 1}
```

In this result, the effects of the first iterations of the loops (for the whole of `t[0]`, the whole of `t[1]` and the first half of `t[2]`) have been computed precisely. The effects on the rest of `t` were computed with approximations. Because of these approximations, the analyzer can not tell whether each of those cells contains 1 or its original value 0. The value proposed for the cells `t[2][5]` and following is imprecise but correct. The set `{0; 1}` does contain the actual value `1` of the cells.

The option `-eva-slevel-function f:n` tells the analyzer to apply semantic unrolling level `n` to function `f`. This fine-tuning option allows to force the analyzer to invest time precisely analyzing functions that matter, for instance `-eva-slevel-function crucial_initialization:2000`. Oppositely, options `-eva-slevel 100 -eva-slevel-function trifle:0` can be used together

to avoid squandering resources over irrelevant parts of the analyzed application. The `-eva-slevel-function` option can be used several times to set the semantic unrolling level of several functions.

Overall, `-eva-slevel` has the advantage of being quick to setup. However, it is in many cases superseded by `-eva-precision`, which controls other parameters related to analysis precision and speed. Also, `-eva-slevel` does not allow fine grained control as loop unrolling annotations, it is context-dependent (e.g. for nested loops), unstable (minor changes in control flow may affect the usage of slevel) and hard to estimate in presence of complex control flows.

Syntactic unrolling

Syntactic unrolling (option `-ulevel n`, provided by the Frama-C kernel), while not recommended when using Eva, is another way to unroll loops for a more precise analysis. The only advantage of syntactic unrolling is that the GUI will show separate statements, allowing the user to see the values of variables at each iteration. However, this method is slower and leads to code which may become less readable, due to the introduction of extra variables, labels and statements.

The value `n` is the number of times to unroll the loop before starting any analysis (if larger than the number of loop iterations, the extra code will still be generated, but it may end up being considered unreachable by Eva). In any case, a large value for `n` makes the analyzed code larger, especially for nested loops. This may cause the analyzer to use more time and memory.

It is possible to control syntactic unrolling for each loop in the analyzed code with the annotation `//@loop pragma UNROLL n;`, placed before the loop.

6.4.2 Widening hints and loop invariants

Besides loop unrolling, another technique to improve precision in loops consists in using the standard computation by accumulation mechanism present in tools based on abstract interpretation. This mechanism requires a more involved setup, but can lead to more efficient analyses.

As compared to loop unrolling, the advantage of the computation by accumulation is that it generally requires less iterations than the number of iterations of the analyzed loop. The number of iterations does not need to be known (for instance, it allows to analyze a `while` loop with a complicated condition). In fact, this method can be used even if the termination of the loop is unclear. These advantages are obtained thanks to a technique of successive approximations. The approximations are applied individually to each memory location in the state. This technique is called "widening". Although the analyzer uses heuristics to figure out the best parameters in the widening process, it may (rarely) be appropriate to help it by providing it with the bounds that are likely to be reached, for a given variable modified inside a loop.

Widening hints

The user may place an annotation `//@ widen_hints` v`,` $e_1, \ldots, e_m$ `;` to indicate the analyzer should use preferably the values $e_1, \ldots, e_m$ when widening the sets of values attached to variable v.

Example:

```
1 int i,j;
2
3 void main(void)
4 {
5   int n = 13;
6   for (i=0; i<n; i++)
7     /*@ widen_hints i, 12, 13; */
8     j = 4 * i + 7;
9 }
```

$e_1, \ldots, e_m$ (the hint *thresholds*) must evaluate to compilation-time constants. They may contain numeric expressions and reference preprocessor macros and `const int` variables. Note that several hints can be added to a single statement, as follows:

```
/*@ widen_hints x, 10, 20, 30;
    widen_hints y, 5, 25; */
```

The user may also annotate a loop with `//@ loop widen_hints` v`,` $e_1, \ldots, e_m$ `;`, in which case v may reference loop iteration variables.

Adding label `global` before the variable name, as in `//@ loop widen_hints global:n,` $e_1, \ldots, e_m$ `;`, makes the annotation affect all loops in all functions, including those from other compilation units. It is useful for referencing variables in inner loops whose outer loop is defined in another file.

Finally, the user may replace the variable name with `"all"` (including the double quotes) to apply the widening hints to *all* variables.

Note that these annotations affect *all* statements in the function, including statements *preceding* the one where the annotation is inserted.

Dynamic widening hints

`widen_hints` annotations accept not only variables, but more generally *lvalues*, such as `*p` and `a[i]->p`. If the lvalue contains a dereference operator, then the widening hint is considered *dynamic*: it is applied to every base pointed to by the lvalue at the statement where the hint is applied. In other words, if the hint `*p, 42` is inside a loop, and at each loop iteration `*p` may point to a new base, then each new base has 42 added to its widening thresholds.

Dynamic hints are automatically global; the `global` prefix must not be applied to them.

Deprecated: `WIDEN_HINTS` loop pragma

This syntax has been deprecated in favor of the previous one and it is kept here only for reference.

The `loop widen_hints` annotation above has an obsoleted syntax:
`//@ loop pragma WIDEN_HINTS` $v_1, \ldots, v_n$`,` $e_1, \ldots, e_m$ `;`
which serves the same purpose but has a few differences:

- it is restricted to loop annotations;
- more than one variable $(v_1, \ldots, v_n)$ can be specified in a single hint;
- if no variables are specified, it works as the special value `"all"`, that is, all variables in the loop are affected;

- it does not accept the global label.

Example:

```
1  int i,j;
2
3  void main(void)
4  {
5    int n = 13;
6    /*@ loop pragma WIDEN_HINTS i, 12, 13; */
7    for (i=0; i<n; i++)
8      j = 4 * i + 7;
9  }
```

Loop invariants

A last technique consists in using the loop invariant construct of ACSL. Loop invariants describe some properties that hold at the beginning of each execution of a loop, as explained in the ACSL specification, §2.4.2. They can be used to gain precision when analyzing loops in the following way: when the analysis is about to widen the value of a variable, it intersects the widened domain with the one inferred through the loop invariant. Thus, the invariant can be used to limit the (possibly overly strong) approximation induced by the widening step.

```
1  #define N 10
2
3  void main (int c)
4  {
5    int t[N+5];
6    if (c >= 1 && c < N)
7    {
8      int *p=t;
9      /*@ loop invariant p < &t[N-1]; */
10     while(1)
11     {
12       *(++p) = 1;
13       if(p >= t+c)
14         break;
15     }
16   }
17 }
```

In the example above, without a loop invariant, the pointer `p` is determined to be in the range `&t + [4..60],0%4`. In C terms, this means that `p` points between `&t[0]` and `&t[15]`, inclusive. In particular, the analysis is not able to prove that the access on line 9 is always valid.

Thanks to the loop invariant `p < &t[N-1]`, the variable `p` is instead widened to the range `&t[0]..&t[N-2]`. This means that the access to `t` through `p` at line 7 occurs within bounds[5]. Thus, this technique is complementary to the use of `WIDEN_HINTS`, which only accepts integers — hence not `&t[N-1]`. Compared to the use of `-eva-slevel` or `-ulevel`, the technique above does not unroll the loop; thus the overall results are less precise, but the analysis can be faster.

Notice that, in the function above, a more precise loop invariant would be

```
5  /*@ loop invariant p < &t[c-1]; */
```

[5] And more precisely between `t[1]` and `t[9]`, since `p` is incremented before the affectation to `*p`.

However, this annotation cannot be effectively used by Eva if the value for `c` is imprecise, which is the case in our example. As a consequence, the analysis cannot prove this improved invariant. We have effectively replaced an alarm, the possible out-of-bounds access at line 7, by an invariant, that remains to be proven.

6.5 Improving precision with case-based reasoning

Some formal proofs about programs require to use *case-based reasoning*. Eva can perform such reasonings through *trace partitioning* [RM07] techniques, which can be enabled globally or by specific annotations. It is important to note that, whatever the method used, a partitioning (and thus the case-based reasoning) currently stops at the end of a function, and can only be extended past the function return if there is enough `slevel` in the calling function.

6.5.1 Automatic partitioning on conditional structures

It sometimes happens that the cases we want to reason on are exactly the cases distinguished in the program by an `if-then-else` statement or a `switch` not far above, even if these blocks are already closed at the point we need the case-based reasoning. Unless enough `slevel` is available, the cases of a conditional structure are approximated together as soon as the analyzer leaves the block. However, Eva can delay this approximation until after the statement where the case-based reasoning is needed.

The global command-line parameter `-eva-partition-history <n>` delays the approximation for all conditional structures of the whole program. The parameter `<n>` controls the delay: it represents the number of junction points for which the incoming paths (the cases) are kept separated. At a given point, Eva is then able to reason by cases on the `<n>` last `if-then-else` statements closed before. A value of 1 means that Eva will reason by case on the previous `if-then-else`, until another one is closed.

This option has a very high cost on the analysis, theoretically doubling the analysis time for each increment of its parameter n. The cost can even be higher on `switch` statements. However, it can remove false alarms in a fully automatic way. Thus, the trade off might often be worth trying.

In practice, `-eva-partition-history 1` seems to be sufficient in most cases, and a greater value is rarely needed.

6.5.2 Value partitioning

Principle

A case-based reasoning on the possible values of an expression can be forced inside a function by using `split` annotations. These annotations must be given an expression whose values correspond to the cases that need to be enumerated. The example below shows a use of this annotation.

```
int t1[] = {1, 2, 3}, t2[] = {4, 5}, t3[] = {6, 7, 8, 9};
int *t[] = {t1, t2, t3};
int sizes[] = {3, 2, 4};
/*@ requires 0 <= i < 3; */
int main(int i)
{
```

```
  int S = 0;
  //@ split i;
  //@ loop unroll sizes[i];
  for (int j = 0 ; j < sizes[i] ; j++)
    S += t[i][j];

  return S;
}
```

The `split` instructs Eva to enumerate all the possible values of `i` and to continue the analysis separately for each of these values. Thereafter, the value of `i` is always evaluated by Eva as a singleton in each case, which enables the use of a `loop unroll` annotation on `i`. This way, the result of the function can be exactly computed as the set of three possible values instead of an imprecise interval.

```
[eva:final-states] Values at end of function main:
  S ∈ {6; 9; 30}
```

A `split` annotation can be used on any expression that evaluates to a *small* number of integer values. In particular, the expression can be a C comparison like in the following example.

```
double fabs(double x)
{
  return x < 0.0 ? -x : x;
}

double main(double y)
{
  //@ split y < 0.0;
  if (fabs(y) > 1.0)
    y = y < 0 ? -1.0 : 1.0;
  //@ merge y < 0.0;
  return y;
}
```

This example requires the equality domain (enabled with option `-eva-domains equality`, see section 6.7.1) to be analyzed precisely, as we need the equality relations between the input and the output of the function `fabs`, i.e. the relations `x == \result` or `x == -\result`. Then, the `split` annotation before the call to `fabs` allows Eva to reason by case and to infer the relevant equality in each case.

This example also illustrates the use of a `merge` annotation, which ends the case-based reasoning started by a previous `split` annotation with the exact same expression. The use of `merge` annotations is not mandatory, but they allow the user to mitigate the cost of `split` annotations.

Static and dynamic partitioning

Two kinds of value partitioning are available:

Static split with annotation `//@ split e;`
: The partitioning is done once at the annotation point: Eva enumerates all possible values of the given expression, and continues the analysis separately for each of these values, until a merge annotation is encountered.

Dynamic split with annotation `//@ dynamic_split e;`
: The partitioning is maintained at each program point according to the current value

of the given expression `e`. At each assignment of a variable on which `e` depends, the partitioning is updated to ensure that the expression always evalutes to a singleton in each analysis state, until a merge annotation is encountered.

A static split allows reasoning according to the value of an expression at the annotation point, while a dynamic split enables reasoning according to the current value of the expression as long as the partitioning is active.

In both following examples, the values of the array `t` are sorted in increasing order, so the value of `t[i+1] - t[i]` is always positive. However, without value partitioning, the analysis computes independently the possible values for `t[i]` and `t[i+1]`, which may have any value in the intervals [0..55] and [1..89] respectively, and `r = t[i+1] - t[i]` may then be negative.

To be precise on these examples, we need to separate the analysis for each value of `i`, so that the accesses to the values of `t` are exact. With such partitioning, the values of `t[i]`, `t[i+1]` and `r` are computed separately for each possible value of `i`.

```
#include "__fc_builtin.h"
void main(void) {
  int t[12] = {0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89};
  int i = Frama_C_interval(0, 10);
  //@ split i;
  int x = t[i];
  int y = t[i+1];
  i = 0;
  int r = y - x;
  //@ assert r >= 0;
  //@ merge i;
}
```

To be precise on this first example, we need a static split on `i`, as the value of `i` is set to 0 before the computation of `r`, but the values of `x` and `y` depend on the previous value of `i`.

```
#include "__fc_builtin.h"
void test2(void){
  int t[12] = {0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89};
  int i = Frama_C_interval(0, 10);
  //@ dynamic_split i;
  while (i < 11) {
    int x = t[i];
    int y = t[i+1];
    int r = y - x;
    //@ assert r >= 0;
    i++;
  }
  //@ merge i;
}
```

In this second example, the value of `r` is computed at each loop iteration and depends on the current value of `i`, which also changes at each loop iteration. So we need a dynamic split to ensure that the analysis separates the new values of `i` during the analysis of the loop.

We could also use a static split in the loop body, to ensure that the partitioning is updated at each loop iteration. On more complex codes where the partitioned value is written or used many times, a single dynamic split is often more suitable than static splits.

Interprocedural value partitioning

By default, the value partitioning performed by `split` and `dynamic_split` annotations is only maintained in the current function: when returning to the caller, the value partitioning finishes and partitioned states are merged together.

The option `-eva-interprocedural-splits` can be used to change this behavior and keep value partitioning through return statements.

Alternatively to annotations, it is also possible to use the command line to perform case-based reasoning throughout the whole analysis. The command-line parameter `-eva-partition-value <v>` forces the analyzer to reason at all times on single values of the global variable `v`, by performing a dynamic split on `v` for the whole analysis.

Limitations

There are four limitations to the value partitioning:

1. Splits can only be performed on integer expressions. Pointers and floating-point values are not supported yet.
2. The expression on which the split is done must evaluate to a small set of integer values, in order to limit the cost of the partitioning and ensure the termination of the analysis. If the number of possible values inferred for the expression exceeds a defined limit, Eva cancels the split and emits a warning. The limit is 100 by default and can be changed with option `-eva-split-limit <n>`.
3. While the number of simultaneous splits (whether local with annotations or global through command line) is not bounded, there can be only one split per expression. If two `split` annotations use the same expression, only the latest one encountered on the path will be kept. Although it is a limitation, it can be used to define strategies where a case-based reasoning is controlled accross the whole program.
4. When the expression is complex, the ability of Eva to reason precisely by cases depends on the enabled abstract domains (see section 6.7) and their capability to learn from the value of the expression. If Eva detects that the expression is too complex for the split to be useful, it will cancel the split and warn the user.

6.6 Controlling approximations

6.6.1 Cutoff between integer sets and integer intervals

Option `-eva-ilevel <n>` is used to indicate the number of elements below which sets of integers should be precisely represented as sets. Above the user-set limit, the sets are represented as intervals with periodicity information, which can cause approximations.

Example:

```
1 #include "__fc_builtin.h"
2
3 int t[12] = {2, 3, 5, 7, 11, 13, 17, 19, 23, 27, 29, 31};
4
5 int main()
6 {
```

```
7   return t[Frama_C_interval(0, 11)];
8 }
```

With the default limit of 8 elements for sets of integers, the analysis of the program shows a correct but approximated result:

```
  __retres ∈ [2..31]
```

Studying the program, the user may decide to improve the precision of the result by adding `-eva-ilevel 16` to the command line. The analysis result then becomes:

```
  __retres ∈ {2; 3; 5; 7; 11; 13; 17; 19; 23; 27; 29; 31}
```

6.6.2 Maximum number of precise items in arrays

Option `-eva-plevel <n>` is used to limit the number of elements in an array that can be considered precisely during assignments. When assigning a value to an array element, if the index is imprecise, it may be very costly to update each array element individually. Instead, if the range of indices to be accessed is larger than *plevel*, some approximations are made and a message is emitted:

```
[kernel] arrays.c:32:
  more than 200(300) elements to enumerate. Approximating.
```

This message means that the array to be updated had 300 elements, and `-eva-plevel` was set to 200 (the default value). In this case, it might be reasonable to increase the plevel to 300, especially if some alarms could be caused by the imprecision. In other cases, however, there is little hope of obtaining a reasonable bound:

```
more than 200(0x20000000) elements to enumerate. Approximating.
```

In some cases, lowering the plevel can improve performance, but it is rarely a significant factor. Most of the time, this option has little impact in the analysis, both in terms of precision and performance. However, when dealing with large arrays and matrices, it is worth considering its usage.

6.7 Analysis domains

This section presents the analysis *domains* available to improve the precision on specific code constructs. They can (and probably should) be enabled at the beginning of the analysis. Their only downside is that they increase the analysis time.

Figure 6.1 presents the list of currently available analysis domains, with a short description of each one. Most domains are also presented in more details in the following subsections.

These analysis domains are enabled by the option `-eva-domains`, followed by a list of domain names. A list of the available domains, and a short description of each one, can be displayed with `-eva-domains help`.

Domains can also be enabled for specific functions through option `-eva-domains-function`:

- `-eva-domains-function d1:f,d1:g,d2:h` enables the domain `d1` on functions `f` and `g`, and the domain `d2` on function `h`.

Name	Log	Ref	Description
cvalue	d-cvalue		Main analysis domain, enabled by default. Should not be disabled.
equality	d-equality	6.7.1	Infers equalities between C expressions. Useful on most analyses and very efficient.
symbolic-locations	d-symblocs	6.7.2	Infers values at symbolic locations. Useful on most analyses and very efficient.
gauges	d-gauges	6.7.3	Infers linear inequalities between variables modified within a loop. Efficient.
octagon	d-octagon	6.7.4	Infers relations between scalar variables. Efficient but limited.
multidim	d-multidim	6.7.5	More precise representation of arrays of structures, multidimensional arrays and arrays invariants. Experimental.
bitwise	d-bitwise	6.7.6	Interprets more precisely some bitwise operations. Rarely useful.
sign	d-sign		Infers the sign of variables. Rarely useful.
apron-box apron-octagon apron-polka-equality apron-polka-loose apron-polka-strict	d-apron	6.7.7	Experimental and often costly. Binding to the Apron library domains.
taint	d-taint	6.7.8	Experimental. Performs a taint analysis.
numerors	d-numerors	6.7.9	Experimental. Infers ranges for absolute and relative errors in floating-point computations.
inout	d-inout		Experimental. Computes the input and output of each function.
traces	d-traces		Experimental. Builds an over-approximation of all traces leading to a statement.
printer	d-printer		Only useful for developers.

Figure 6.1: Analysis domains

- `-eva-domains-function d:f+` enables the domain `d` on function `f` and on any function called from `f`.
- `-eva-domains-function d:f-` disables the domain `d` on function `f` and on any function called from `f`.

These analysis domains currently have some restrictions:

- adding a new domain may interact with the `slevel` partitioning in unpredictable ways, and new alarms may sometimes appear;
- the properties inferred by these domains cannot be easily viewed in the GUI; only a few domains have their values printed in the *Values* tab.

However, the properties inferred by a specific domain at a program point may be inspected by using the directive `Frama_C_dump_each` or `Frama_C_domain_show_each` in the analyzed source code, and by enabling the log category of the given domain. These directives are described in Section 9.3, and the log category of each domain is given by Figure 6.1.

6.7.1 Symbolic equalities

Activating option `-eva-domains equality` instructs Eva to perform a special analysis that stores information about equalities found in the code. Those equalities may stem either from conditions (e.g. `if (x == y+1)`), or assignments `y = x+2;`. Once an equality has been inferred, it will be used when one of the expressions involved occurs later in the program.

```
  int y = x+1;
  // the equality y == x + 1 is inferred
  if (y <= 2) {
    // Thanks to the equality, x <= 1 is deduced
  }
}
```

This domain should be activated by default. Indeed, the normalisation done by Frama-C for expressions with side-effects introduces temporary variables, for which the equality domain is useful to regain precision.

By default, the analysis is partially inter-procedural. At the end of a call, equalities inferred in the called function are always propagated back to the caller. At the beginning of a call, the option `-eva-equality-through-calls` controls which equalities from the caller are propagated to the called function. Three global modes are available:

none No equality is propagated to called functions. Faster but less precise mode.

formals Default mode: only the equalities between the formal parameters and the actual arguments of the call are used at the beginning of a function.

all All equalities from the call site are used when analyzing a called function. This slows down the analysis, and should only be set for specific functions through the option `-eva-equality-through-calls-function`.

6.7.2 Reused left-values

Activating option `-eva-domains symbolic-locations` instructs Eva to perform a special analysis for *reused left-values*.

```
int t[10];

extern unsigned int u[10];

//@ requires i < 10;
void main(unsigned int i) {
  if (u[i] < 8) {
    t[u[i]] = 2;
  }
}
```

On this code, Eva cannot represent precisely `u[i]`, and "learns" nothing from the condition `u[i] < 8`. Hence, Eva emits an alarm on the line `t[u[i]] = 2`, as it cannot prove that `u[i]` is less than 10.

To allow learning information from such conditionals, the new analysis stores information especially for `u[i]` itself. This analysis is of course correct in presence of pointers, in particular when the left-value is written through an alias between two read accesses. All "compound" left-values such as `u[i]`, `*p` or `q->t[i].v` are handled.

Currently, the analysis is intra-procedural. The information known in the caller is not propagated in the callee.

6.7.3 Gauges

Activating option `-eva-domains gauges` instructs Eva to store relations between integer (or pointer) variables modified by a loop, and the number of elapsed loop iterations. It is based on the paper *"The Gauge Domain: Scalable Analysis of Linear Inequality Invariants"* [Ven12].

```
int y = 3;
int t[100];
int *p = &t[0];

for (int i=0; i<100; i++) {
  y += 2; // y == 2*i + 5 holds. In particular, y <= 203
  *p++ = i; // all accesses are in bound
}
```

This domain should be activated for programs in which finite loops increase multiple variables simultaneously, in an affine way. It is *not* useful if the loop is fully unrolled by syntactic or semantic means, or if the relation between variables is not affine (e.g. computing a square).

```
  if (x++ <= 10) { ... }

// Transformed into

  int tmp = x;
  x++;
  if (tmp <= 10) { // Nothing is learnt on x without the
                   // domain of equalities }
```

Currently, the analysis is intra-procedural only: no information flows from the caller to the callee, or in the reverse direction. The relations inferred can only involve variables that are:

- local to a function (e.g. not a global), and not `static`;
- scalar (not a field of a struct, or a cell in an array).

Beware that the analysis works better when arithmetic overflows are reported as an alarm. With the default options of Frama-C, this means that gauges can be inferred easily for *signed* variables, but less so for *unsigned* ones. Indeed, the affine relations inferred by the domain are no longer true once the variable exceeds e.g. `INT_MAX` and wraps. Code such as

```
unsigned int x = ...;
int y = ...;

while (--x > 0) {
  y++;
  [...]
}
```

cannot be analyzed precisely, because the relation between `x` and `y` is not affine.

6.7.4 Octagons

Activating option `-eva-domains octagon` instructs Eva to infer relations between variables as numerical constraints of the form $l \leq \pm X \pm Y \leq u$, where X and Y are program variables, and l and u are constants.

These relations are then used to evaluate more precisely the possible values of an expression involving X and Y, or to deduce a reduction of the possible values of X from a reduction of the possible values of Y.

The following code is a minimal working example that illustrates the precision improvement provided by the octagon domain.

```
void main (int y) {
  int k = Frama_C_interval(0, 10);
  int x = y - k;             // y - x ∈ [0..10]
  int r = x + 3 - y;         // r ∈ [-7..3]
  int t;
  if (y > 15)
    t = x;                   // t ∈ [6..∞]
}
```

Currently, the octagon domain is fast but has two strong limitations:

- The domain only infers relations between scalar variables of integer types. It ignores pointers, arrays and structure fields.
- The domain only infers relations between pairs of variables occurring in the same instruction, as `x = y + k;` or `if (x < y + k)`. If an instruction involves 3 variables or more, relations are inferred for each pair of variables.

The domain is intraprocedural by default: the inferred relations are local to the current function and are lost when entering a function call or returning to its caller.

The option `-eva-octagon-through-calls` makes the octagon domain interprocedural, which is a more precise but slower mode where the inferred relations are propagated through function calls. The analysis of a function can then use the relations inferred in the callers, and at the end, the inferred relations are propagated back to the caller.

6.7.5 Multidim

This domain is experimental.

The multidim domain implements a typed memory model designed to abstract multidimensional arrays, arrays of structures, or any composition of any depth of these. It can also infer simple array invariants on simple program loops.

The domain is less precise than the cvalue domain when array properties need to be inferred cell by cell. However, it may often be more precise on large arrays of structures, especially when the indexes at which these arrays are written cannot be reduced to singleton values with usual techniques such as loop unrolling.

The domain abstracts arrays by summarizing them with a *segmentation*, i.e. a partition of *segments*. A segment is a set of arrays cells with consecutive indexes. A classical segmentation would be the division of an array into three segments arround a program variable `i`: the set of cells whose index is lower than `i`, the singleton cell of index `i` and the set of cells whose index is greater than `i`.

The segments are then abstracted separately, allowing the analyzer to infer distinct properties for each segment. Inside a segment, the inferred properties are valid for all cells of the segment.

Furthermore, arrays of structures are approximated field by field, allowing the inference of precise invariants about each field of all structures included in the array. More generally, a (multidimensional) array of structures is abstracted by a tree where:

- each node is a set of offsets,
- each depth of the tree corresponds to an array or structure type,
- *array nodes* have an associated segmentation and a child for each segment,
- *structures nodes* have a child for each field of the structure.

This model keeps track of the types used to write to the memory, and thus can display the contents of the memory with its structure (via `Frama_C_domain_show_each` directives), even when the underlying location type does not always match the types used to write into it.

The domain tries to infer a suitable partition in a best-effort strategy. It will work on most simple loops, but may fails outside the most common patterns.

Two command-line options and one annotation can be used to configure the domain.

- `-eva-multidim-disjunctive-invariants` can be used to infer disjunction invariants on C structures when a field of a structure is assigned a constant value and the invariant of the structure depends on this value.
- `-eva-multidim-segment-limit` can be used to increase the limit on the number of segments allowed in the array partitions, when the default limit of 8 is too low.

- The annotation `array_partition` can be used to help the domain to find a suitable segmentation for the analysis. For instance, in the following example, the annotation instructs the analyzer to use 3 segments for the analysis of the loop.

```
int t[20] = {0};
//@ array_partition t, 0, i, i+1, 20;
for (int i = 0; i < 20; i++) {
  ...
}
```

  When the annotation is encountered, the current array partition is replaced by the given one, and the introduced segment bounds are kept as long as possible. When a subsequent array access uses an index than cannot be proven to be always below or above such a bound, this bound is removed.

6.7.6 Bitwise values

This analysis is experimental.

Activating option `-eva-domains bitwise` instructs Eva to store bitwise information in complement to the usual, interval-based, information. This is mostly useful for programs that use bitwise operators: `&`, `|`, `^` and `~`, especially with bit-masks constants. The following program is analyzed more precisely thanks to the bitwise domain (with `-eva-slevel 2`).

```
int isTopBit(unsigned something)
{
  //@ assert something >= 0x80000000 || something < 0x80000000;
  unsigned topBitOnly = something & 0x80000000;
  something ^= topBitOnly;
  if (something & 0x80000000) // More precision on this conditional { ... }
}
```

The current analysis is fully inter-procedural. All variables (including aggregates and arrays) are handled. However, for conciseness, the domain tries not to track information which is redundant with the intervals-based domain. In some cases, the domain is able to infer precise information on the bits of a pointer address.

6.7.7 Binding to APRON

These bindings are proofs-of-concept.
They require the ***apron*** *library, provided by opam.*

Eva features a very experimental binding to the numerical domains of the APRON library [JM09]. Assuming Frama-C has been compiled with support for Apron, the corresponding options are:

-eva-domains apron-box : boxes/intervals

-eva-domains apron-octagon : octagons

-eva-domains apron-polka-equality : linear equalities

-eva-domains apron-polka-loose : loose polyhedra

-eva-domains apron-polka-strict : strict polyhedra

The analysis is fully interprocedural. However, the binding is currently intended as a proof-of-concept, and should probably be used on small examples–not on full-scale programs. In particular, the following restrictions apply to the current implementation:

- only integer variables are tracked (pointers, floating-point values, and array cells or aggregate fields are ignored);
- variables are *not* packed, which may result in a very large number of tracked variables. Since relational domains are usually costly (cubic complexity for octagons, exponential for polyhedra), this may result in very long analyses and/or massive memory usage.

6.7.8 Taint

This domain is experimental.

Option `-eva-domains taint` performs a taint analysis, which is a data-dependency analysis tracking the impact an external user may have on the program execution when supplying some data.

The initial taint must be specified by the user with ACSL annotations `//@ taint <lvalues>;` on a statement, or a clause `taints <lvalues>;` in a function contract.

These directives are hypotheses of the taint analysis, and thus have no logical status. The specified set of lvalues becomes tainted just after the code annotation, or at the return of the function with the `taints` clause.

```
int r = write(buf, n);
//@ taint r, buf[0..n];
```

```
/*@ requires \valid(buf + (0..n));
    assigns \result, *p, buf[0..n];
    ensures 0 <= \result < n;
    taints \result, buf[0..n]; */
    int write(char *buf, int n);
```

The taint is then propagated during the Eva analysis, which computes an over-approximation of the set of tainted locations at each program point.

The ACSL predicate `\tainted` can be used to verify that some values are *not* tainted. Indeed, the domain only infers over-approximations of the tainted locations: while locations in the over-approximations *may be* tainted, all other locations are proven to be safe.

```
void fun(int a, int b, int t) {
  //@ taint t;
  int x = a + t;
  int y = a - b;
  //@ assert \tainted(x);   // UNKNOWN
  //@ assert !\tainted(y);  // TRUE
}
```

The `\tainted` predicate can also be used to reduce the over-approximation of the tainted locations, by asserting that some values are not tainted anymore.

```
/*@ ensures !\tainted(*p); */
void sanitize(int *p);
```

6.7.9 Numerors

This domain is experimental and should only be used on toy examples.
It requires the `mlgmpidl` library with support of MPFR, provided by opam.

Eva provides a domain inferring ranges for the absolute and relative errors stemming from floating-point computations. This domain can be enabled by the option `-eva-domains numerors`. The theory and core principles underlying this domain are described in [JPV18].

The errors inferred by the domain can be seen in the GUI, alongside the other values inferred by Eva. For each selected floating-point variable or expression, the numerors domain shows over-approximations of:

- its real value, computed by over-approximation of the mathematical semantics;
- its floating-point value, computed accordingly to the IEEE 754 standard;
- its absolute error, i.e. the possible difference between the real value and the floating-point value;
- its relative error, i.e. the absolute error divided by the real value.

Current limitations The numerors domain does not handle loops, unless they are completely unrolled by the analysis. Floating-point computations occurring within loops are interpreted as leading to any possible value.

Moreover, the domain only infers error values for scalar variables. Structure and union fields, as well as arrays, are ignored.

6.8 Non-termination

The parameterization of Eva can lead to situations where the analysis stops abruptly due to the absence of valid states. For instance, some primitives (section 9) may detect an invalid precondition and stop propagating the current callstack, or a loop may become infinite if the exit condition depends on invalid accesses.

The alarms generated in these situations may become *Unknown* if there are other callstacks for which the analysis succeeded. Therefore, during the initial part of an analysis, they may blend in with the sets of possibly false alarms. However, priority should be given to these alarms, since they are likely to indicate an incorrect parameterization.

To help identify these situations, the Nonterm plug-in has been developed. It runs after Eva, by adding `-then -nonterm` at the end of the command-line.

Nonterm emits warnings about non-terminating instructions in functions analyzed by Eva. It operates on a per-callstack basis, and therefore displays more precise results than a visual inspection on the GUI; in particular, if there are both terminating and non-terminating callstacks for a given statement, the GUI will not color their successors red (because of the terminating callstacks), but Nonterm will emit warnings for the non-terminating ones.

Nonterm only reports situations where Eva is able to guarantee non-termination. Because its purpose is to prioritize warnings that are likely to indicate parameterization errors, it does not consider callstacks where termination seems possible.

To avoid too much noise, you can use `-nonterm-ignore f1,f2,f3,...` to indicate functions that should not be reported by the plug-in. By default, `abort` and `exit` are always ignored (you can override this via `-nonterm-ignore=-abort,-exit`).

Also, option `-nonterm-dead-code` enables the emission of warnings related to syntactically unreachable code, e.g. instructions that are unreachable due to `goto`s or unconditional breaks. This can however generate a substantial amount of warnings and is rarely needed in practice.

Chapter 7

Inputs, outputs and dependencies

Frama-C can compute and display the inputs (memory locations read from), outputs (memory locations written to), and precise dependencies between outputs and inputs, for each function. These computations use Eva for resolving array indices and pointers.

7.1 Dependencies

An example of dependencies as obtained with the option `-deps` is as follows:
`y FROM x; z (and SELF)`

This clause means that in this example, the variable `y` may have changed at the end of the function, and that the variables `x` and `z` are used in order to compute the new value of `y`. The text "`(and SELF)`" means that `y` *might* have been modified, and that if it had, its new value would only depend on `x` and `z`, whereas the absence of such a mention means that `y` has necessarily been overwritten.

The dependencies computed by `-deps` hold if and when the function terminates. The list of variables given for an output `y` contains all variables whose initial values can influence the final value of `y`.

Dependencies are illustrated in the following example:

```
1 int b,c,d,e;
2
3 void loop_branch(int a)
4 {
5   if (a)
6     b = c;
7   else
8     while (1) d = e;
9 }
```

The dependencies of function `loop_branch` are `b FROM c`, which means that when the function terminates, the variable `b` has been modified and its new value depends on `c`. The variables `d` and `e` do not appear in the dependencies of `loop_branch` because they are only used in branches that do not terminate. A function for which the analyzer is able to infer that it does not terminate has empty dependencies.

The set of variables that appear on the right-hand side of the dependencies of a function are called the "functional inputs" of this function. In the example below, the dependency of `double_assign` is `a FROM c`. The variable `b` is not a functional input because the final value of `a` depends only on `c`.

```
int a, b, c;

void double_assign(void)
{
  a = b;
  a = c;
}
```

The dependencies of a function may also be listed as `NO EFFECTS`. This means that the function has no effects when it terminates. There are various ways this can happen; in the example below, all three functions `f`, `g` and `h` get categorized as having no effects. Function `f` does it the intuitive way, by not having effects. Function `g` and `h` get categorized as not having effects in a more subtle way: the only executions of `g` that terminate have no effects. Function `h` never terminates at all, and neither `*(char*)0` nor `x` and `y` need be counted as locations modified on termination.

```
int x, y;

void f(void)
{
  0;
}

void g(int c)
{
  if (c)
  {
    x = 1;
    while (x);
  }
}

void h(void)
{
  x = 1;
  y = 2;
  *(char*)0 = 3;
}
```

7.2 Imperative inputs

The imperative inputs of a function are the locations that may be read during the execution of this function. The analyzer computes an over-approximation of the set of these locations

with the option `-input`. For the function `double_assign` of the previous section, Frama-C offers `b; c` as imperative inputs, which is the exact answer.

A location is accounted for in the imperative inputs even if it is read only in a branch that does not terminate. When asked to compute the imperative inputs of the function `loop_branch` of the previous section, Frama-C answers `c; e` which is again the exact answer.

Variant `-input` omits function parameters from the displayed inputs.
Variant `-input-with-formals` leaves function parameters in the displayed inputs (if they indeed seem to be accessed in the function).

7.3 Imperative outputs

The imperative outputs of a function are the locations that may be written to during the execution of this function. The analyzer computes an over-approximation of this set with the option `-out`. For the function `loop_branch` from above, Frama-C provides the imperative outputs `b; d` which is the exact answer.

Variant `-out` includes local variables, and variant `-out-external` omits them.

7.4 Operational inputs

The name "operational inputs of a function" is given to the locations that are read without having been previously written to. These are provided in two flavors: a superset of locations that can be thus read in all terminating executions of the function, and a superset of the locations thus read including non-terminating executions.

Operational inputs can for instance be used to decide which variables to initialize in order to be able to execute the function. Both flavors of operational inputs are displayed with the option `-inout`, as well as a list of locations that are guaranteed to have been over-written when the function terminates; the latter is a by-product of the computation of operational inputs that someone may find useful someday.

```
1  int b, c, d, e, *p;
2
3  void op(int a)
4  {
5    a = *p;
6    a = b;
7    if (a)
8      b = c;
9    else
10     while (1) d = e;
11 }
```

This example, when analyzed with the options `-inout -lib-entry -main op`, is found to have on termination the operational inputs `b; c; p; S_p[0]` for function `op`. Operational inputs for non-terminating executions add `e`, which is read inside an infinite loop, to this list.

Variable `p` is among the operational inputs, although it is not a functional input, because it is read (in order to be dereferenced) without having been previously overwritten. The variable `a` is not among the operational inputs because its value has been overwritten before being read. This means that an actual execution of the function `op` requires to initialize `p` (which

influences the execution by causing, or not, an illicit memory access), whereas on the other hand, the analyzer guarantees that initializing `a` is unnecessary.

Chapter 8

Annotations

Frama-C's language for annotations is ACSL. Only a subset of the properties that can be expressed in ACSL can effectively be of service to or be checked by the Eva plug-in.

If you are not familiar with ACSL, consider reading the *ACSL Quick Guide for Eva*, in Appendix A. It contains a brief introduction to ACSL, targeted towards Eva users. Even if you already know some ACSL, it contains a few Eva-related remarks and tips related to specific warnings, which might be useful.

8.1 Preconditions, postconditions and assertions

8.1.1 Truth value of a property

Each time it encounters a precondition, postcondition or user assertion, the analyzer evaluates the truth value of the property in the state it is propagating. The result of this evaluation can be:

- `valid`, indicating that the property is verified for the current state;
- `invalid`, indicating that the property is certainly false for the current state;
- `unknown`, indicating that the imprecision of the current state and/or the complexity of the property do not allow to conclude in one way or the other.

If a property obtains the evaluation `valid` every time the analyzer goes through it, this means that the property is valid under the hypotheses made by the analyzer.

When a property evaluates to `invalid` for some passages of the analysis, it does not necessarily indicate a problem: the property is false only for the execution paths that the analyzer was considering these times. It is possible that these paths do not occur for any real execution.

The fact that the analyzer is considering these paths may be a consequence of a previous approximation. However, if the property evaluates to `invalid` for *all* passages of the analysis, then the code at that point is either dead or always reached in a state that does not satisfy the property, and the program should be examined more closely.

The analysis log contains property statuses relative to the state currently propagated (this is to help the user understand the conditions in which the property fails to verify). The same property can appear several times in the log, for instance if its truth value is `valid` for some passages of Eva and `invalid` for others.[1]

The graphical interface also displays a summary status for each property that encompasses the truth values that have been obtained during all of the analysis.

8.1.2 Reduction of the state by a property

After displaying its estimation of the truth value of a property P, the analyzer uses P to refine the propagated state. In other words, the analyzer relies on the fact that the user will establish the validity of P through other means, even if it itself is not able to ensure that the property P holds.

Let us consider for instance the following function.

```
1  int t[10],u[10];
2
3  void f(int x)
4  {
5    int i;
6    for (i=0; i<10; i++)
7      {
8        //@ assert x >= 0 && x < 10;
9        t[i] = u[x];
10     }
11 }
```

```
frama-c -eva -eva-slevel 12 -lib-entry -main f reduction.c
```

Eva emits the following two warnings:

```
reduction.c:8: warning: Assertion got status unknown.
reduction.c:8: warning: Assertion got status valid.
```

The first warning is emitted at the first iteration through the loop, with a state where it is not certain that `x` is in the interval `[0..9]`. The second warning is for the following iterations. For these iterations, the value of `x` is in the considered interval, because the property has been taken into account at the first iteration and the variable `x` has not been modified since. Similarly, there are no warnings for the memory access `u[x]` at line 9, because under the hypothesis of the assertion at line 8, this access may not cause a run-time error. The only property left to prove is therefore the assertion at line 8.

Case analysis

When using *slevel-based unrolling* (section 6.4.1), if an assertion is a disjunction, then the reduction of the state by the assertion may be computed independently for each disjunct. This

[1] Conversely, as Frama-C's logging mechanism suppresses the printing of identical message, the property is printed only once with each status.

multiplies the number of states to propagate in the same way that analyzing an `if-then-else` construct does. Again, the analyzer keeps the states separate only if the limit (the numerical value passed to option `-eva-slevel`) has not been reached yet in that point of the program.

This treatment often improves the precision of the analysis. It can be used with tautological assertions to provide hints to the analyzer, as shown in the following example.

```
1  #include "__fc_builtin.h"
2
3  int main(void)
4  {
5    int x = Frama_C_interval(-10, 10);
6    //@ assert x <= 0 || x >= 0 ;
7    return x * x;
8  }
```

```
frama-c -eva -eva-slevel 2 sq.c
```

The analysis finds the result of this computation to be in `[0..100]`. Without the option `-eva-slevel 2`, or without the annotation on line 4, the result found is `[-100..100]`. Both are correct. The former is optimal considering the available information and the representation of large sets as intervals, whereas the latter is approximated.

Limitations

Attention should be paid to the following two limitations:

- a precondition or assertion only adds constraints to the state, i.e. always makes it smaller, not larger. In particular in the case of a precondition for a function analyzed with option `-lib-entry`, the precondition can only reduce the generic state that the analyzer would have used had there not been an annotation. It cannot make the state more general. For instance, it is not possible to use a precondition to add more aliasing in an initial state generated by option `-lib-entry`, because it would be a generalization, as opposed to a restriction;
- the interpretation of an ACSL formula by Eva may be approximated. The state effectively used after taking the annotation into account is a superset of the state described by the user. In the worst case (for instance if the formula is too complicated for the analyzer to exploit), this superset is the same as the original state. In this case, it appears as if the annotation is not taken into account at all.

The two functions below illustrate both of these limitations:

```
1  //@ requires a == &b || a == &c;
2  int generalization(int *a, int b, int c)
3  {
4    b = 5;
5    c = 4;
6    *(int*)a = 3;
7    return b;
8  }
9
10 //@ requires d != 0;
11 int not_reduced(int d)
12 {
```

```
13    return d;
14  }
```

If the analyzer is launched with options `-lib-entry -main generalization`, the initial state generated for the analysis of function `generalization` contains a pointer for the variable `a` in a separated memory region.
The precondition `a == &b || a == &c` will probably not have the effect expected by the user: the intention appears to be to generalize the initial state, which is not possible.

If the analyzer is launched with options `-main not_reduced`, the result for variable `d` is the same as if there was no precondition. The interval computed for the returned value, `[--..--]`, seems not to take the precondition into account because the analyzer cannot represent the set of non-zero integers. The set of values computed by the analyzer remains correct, because it is a superset of the set of the value that can effectively happen at run-time with the precondition. When an annotation appears to be ignored for the reduction of the analyzer's state, it is not in a way that could lead to incorrect results.

8.1.3 An example: evaluating postconditions

To treat the postconditions of a function, the analysis proceeds as follows. Let us call B the memory state that precedes a call to a function f, and A the state before the post-conditions[2], *i.e* the union of the states on all `return` statements. Postconditions are evaluated in succession. Given a postcondition P, the analyzer computes the truth value $\mathcal{V}$ of P in the state A. Then:

- If $\mathcal{V}$ is `valid`, the analysis continues on the next postcondition, using state A.
- If $\mathcal{V}$ is `unknown`, the postcondition may be invalid for some states $A_I \subset A$. The analyzer attempts to reduce A according to P, as explained in section 8.1.2. The resulting state A_V is used to evaluate the subsequent postconditions. Notice that P does *not* necessarily hold in A_V, as reduction is not guaranteed to be complete.
- if $\mathcal{V}$ is `invalid`, the postcondition is invalid for all the real executions that are captured by B, and reducing by P leads to an empty set of values. Thus, further postconditions are skipped, and the analyzer assumes that the call did not terminate.

  Notice that an `invalid` status can have three origins:

  ▷ The postcondition is not correct, *i.e* it does not accurately reflect what the body of the function does. Either the postcondition or the body (or both!) can actually be incorrect with respect to what the code is intended to do.

  ▷ The call to f never terminates, but the analyzer has not been able to deduce this fact, due to approximations. Thus, the postcondition is evaluated on states A that do not match any real execution.

  ▷ The entire call actually never takes place on a real execution (at least for the states described by B). This is caused by an approximation in the statements that preceded the call to f.

  In all three cases, $\mathcal{V}$ is recorded by Frama-C's kernel, for further consolidation.

[2] B and A stand respectively for *before* and *after*.

8.2 Assigns clauses

An assigns clause in the contract of a function indicate which variables may be modified by the function, and optionally the dependencies of the new values of these variables.

In the following example, the assigns clause indicates that the `withdraw` function does not modify any memory cell other than `p->balance`. Furthermore, the final value of `p->balance` has been computed only through its initial value and the value of the parameter `s`. The computation of `p->balance` *indirectly* requires reading `p`, as explained below.

```
typedef struct { int balance; } purse;

/*@ assigns p->balance \from p->balance, s, (indirect:p); */
void withdraw(purse *p,int s) {
  p->balance = p->balance - s;
}
```

Direct and indirect from clauses Eva makes use of specifications that are more precise than the ACSL language specifies in that it establishes a distinction between *direct* and *indirect* dependencies. A dependency is direct if the value contained in the dependency impacts the value of the lvalue referred to in the assign clause; a dependency is indirect if the value is used only in a conditional or to compute an address. Indirect dependencies are distinguished by an "indirect" label; other dependencies are direct. See for instance the valid ACSL contract below.

```
/*@ assigns *b \from a, (indirect:c), (indirect:b); */
void f_valid(int a, int *b, int c){
  if (c) {
    *b = a;
  }
  else
    *b = 0;
}
```

An assigns clause can describe the behavior of functions whose source code is not part of the analysis project. This happens when the function is really not available (we call these "library functions") or if it was removed on purpose because it did something that was complicated and unimportant for the analysis at hand.

Eva uses the assigns clauses provided for library functions. It does not take advantage of the assigns clauses of functions whose implementation is also available, except when option `-eva-use-spec` is used (section 6.3.10). The option `-from-verify-assigns` can be used to check the assigns clauses, when dependencies computation is also activated (section 7.1).

The effect of an assigns clause `assigns loc \from locD, (indirect:locI)` on a memory state S are modelled by the analyzer as follows:

1. the contents of `locD` in S are evaluated into a value v;
2. v is *generalized* into a value v'. Roughly speaking, scalar values (integer or floating-point) are transformed into the set of all possible scalar values. Pointer values are transformed into pointers on the same memory base, but with a completely imprecise offset.
3. `loc` is evaluated into a set of locations L;

4. each location $l \in L$ of S is updated so that it contains the values present at l in S, but also v'. This reflects the fact that l *may* have been overwritten.

5. furthermore, if `loc` and `locD` are distinct locations in S, the locations in L are updated to contain *exactly* v'. Indeed, in this case, `loc` is necessarily overwritten.[3]

Notice that the values written in `loc1` are *entirely* determined by `locD` and S. Eva does not attempt to "invent" generic values, and it is very important to write \from clauses that are sufficiently broad to encompass all the real behaviors of the function.

Assigns clauses and derived analyses For the purposes of options `-deps`, `-input`, `-out`, and `-inout`, the assigns clauses provided for library functions are assumed to be accurate descriptions of what the function does. For the latter three options, there is a leap of faith in the reasoning: an assigns clause only specifies *functional* outputs and inputs. As an example, the contract `assigns \nothing;` can be verified for a function that reads global `x` to compute a new value for global `y`, before restoring `y` to its initial value. Looking only at the prototype and contract of such a function, one of the `-input`, `-out`, or `-inout` computation would mistakenly assume that it has empty inputs and outputs. If this is a problem for your intended use of these analyses, please contact the developers.

Postconditions of library functions When evaluating a function contract, Eva handles the evaluation of a postcondition in two different ways, depending on whether the function f being evaluated has a source body or just a specification.

Functions with a body First, the body of f is evaluated, in the memory state that precedes the call. Then the analyzer evaluates the postconditions and computes their truth values, following the approach outlined in section 8.1.3. The memory state obtained after the evaluation of the body may also be reduced by the postconditions. After the evaluation of each property, its truth value for this call is printed on the analysis log.

Functions with only a specification The analyzer evaluates the assigns ... \from ... clauses of f, as explained at the beginning of this section. This results in a memory state S that corresponds to the one after the analysis of the hypothetical body of f. Then, since postconditions cannot be proven correct without a body, they are *assumed* correct, and Eva does not compute their truth values. Accordingly, no truth value is output on the analysis log, except when we suspect the postcondition of being incorrect.

Although the analyzer does *not* use the postconditions to create the final memory state, it interprets them in order to *reduce*. Hence, it becomes possible to constrain a posteriori the very broad state S. A typical contract for a function successor[4] would be

```
1 /*@ assigns \result \from x;
2     ensures \result == x + 1; */
3 int succ(int x);
```

Note that postconditions are used solely to *reduce* S, but cannot be used to express the changes of a variable; thus it is very important to write assigns ... \from ... clauses that are correct (broad enough). Without them, the postcondition would apply on the

[3] A correct assigns clause for a function that either writes `y` into `x`, or leaves `x` unchanged, is `assigns x \from y, x;`.

[4] Ignoring problems related to integer overflow.

initial values of the variable when the function is called, not on values produced by the function. For instance, forgetting to write the assign clause for `p` in function `f` would stop the evaluation (the postcondition of `f` is false if `p` is not assigned).

```
    int y; int *p;
    /*@ ensures p == &y; */
    void f(void);
    void main(void){ f(); }
```

Similarly, forgetting the \from clause in the contract for `g` would stop the evaluation (without knowing where the value of `p` comes from, Eva assumes that it points to a constant address).

```
    int y; int *p;
  /*@  assigns p \from q;
       ensures p == &y; */
void g(int *q);
void main(void){ g(&y); }
```

A tricky example is the specification of a function that needs to return the address of a global variable.

```
int x;

void *addr_x(); // Returns (void*)&x;
```

The specification `assigns \result \from &x;` is unfortunately incorrect, as \from clauses can only contain lvalues. Instead, the following workaround can be used:

```
int x;
int * const __p_x = &x;

/*@ assigns \result \from __p_x;
    ensures \result == &x; */
void *addr_x();
```

8.3 Specifications for functions of the standard library

Basic implementations are provided for some functions of the C standard library, within the files `$SHARE/frama-c/libc/*.c`. Specifications are also available for those functions in the files `$SHARE/frama-c/libc/**.h`. When analyzing a program where both the specification and the implementation are available, the implementation "takes precedence". That is, specifications are completely ignored by Eva. Indeed, the analysis of the body is usually more precise. Also, in some cases, the specifications use involved ACSL constructs that are currently not understood by Eva.

It is possible to change this behavior, and to analyze both the implementation and the specification, using option `-eva-no-skip-stdlib-specs`. Beware that when this option is not set, even user-written specifications are skipped (for functions of the standard library).

Chapter 9

Primitives

It is possible to interact with the analyzer through insertion in the analyzed code of calls to pre-defined functions.

There are three reasons to use primitive functions: emulating standard C library functions, transmitting analysis parameters to the plug-in, and observing results of the analysis that wouldn't otherwise be displayed.

9.1 Standard C library

The application under analysis may call functions such as `malloc`, `strncpy`, `atan`,... The source code for these functions is not necessarily available, as they are part of the system rather than of the application itself. In theory, it would be possible for the user to give a C implementation of these functions, but those implementations might prove difficult to analyze for the Eva plug-in. A more pragmatic solution is to use a primitive function of the analyzer for each standard library call that would model as precisely as possible the effects of the call.

Currently, the primitive functions available this way are all inspired from the POSIX interface. It would however be possible to model other system interfaces. Existing primitives are described in the rest of this section.

Builtins are enabled by default. The currently available builtins include some string functions (e.g. `strlen` and `strnlen`), some floating-point mathematical functions (e.g. `sin` and `pow`), and functions for dynamic memory allocation (`malloc`, `calloc`, `realloc` and `free`). The complete list of builtins for Eva (including builtins unrelated to the standard C library) is presented in section 9.4. You can also use option `-eva-builtins-list` to obtain the list of function names mapped to builtins, as well as the list of all builtins.

You can also manually specify each builtin to be used with option `-eva-builtin`, which takes pairs of functions: the function to be replaced, and the name of the builtin that replaces it. For

instance, option `-eva-builtin sin:Frama_C_sin,strlen:Frama_C_strlen` enables builtins for the `sin` and `strlen` functions of the standard library. Note that even if a builtin is specified this way, the function still needs to be declared to be used. Also, note that existing implementations are ignored for functions replaced with builtins. If you want Eva to use your own definition of a function such as `strlen`, for instance, you need to use option `-eva-no-builtins-auto`. You can then manually enable `-eva-builtin` for each builtin that you do wish to activate.

Specifications for replaced functions. For the verification to be complete, functions replaced by builtins *must* come with the preconditions and `assigns`/`from` clauses[1] that accompany them in the standard library of Frama-C. Eva will then evaluate them, and set validity statuses on them (Section 8). When standard headers are used, this is done automatically. If you use option `-no-frama-c-stdlib`, and/or write yourself the prototypes of the C functions, you *must* duplicate the relevant part of the specification. For most functions, this is immediate. However, for a few functions –such as string-related ones– you must also duplicate the definitions of the logic predicates used to write the preconditions, as shown below:

```
#define __PUSH_FC_STDLIB #pragma fc_stdlib(push,__FILE__)
#define __POP_FC_STDLIB #pragma fc_stdlib(pop)

__PUSH_FC_STDLIB

/*@ axiomatic StrLen {
  @ logic  real  strlen{L}(char *s) reads s[0..];
  @ }
*/

/*@ predicate valid_read_string{L}(char *s) =
  @   0 <= strlen(s) && \valid_read(s+(0..strlen(s)));
*/

__POP_FC_STDLIB

/*@ requires valid_read_string(str);
    assigns  \result  \from str[0..]; */
size_t strlen(const char * str);
```

9.1.1 `malloc`, `calloc`, `realloc` and `free` functions

Several builtins for modeling dynamic allocation are available in Frama-C. Different variants are provided to allow precise results when possible, and convergence (termination) when needed. Some differences between the *strong* and *weak* bases allocated by these builtins are explained in section 5.6.4.

Option `-eva-alloc-builtin` selects the behavior for allocation builtins, among the following:

`by_stack` : create a few bases per callstack (the exact number is given by option `-eva-mlevel`, detailed later). Always converges. This is the default value.

`fresh` : create a new strong base for each call. The most precise builtin, but may not converge (e.g. when called inside a loop).

[1] All other kind of clauses, including post-conditions, are ignored.

`fresh_weak` : like the previous one, but using weak bases.

`imprecise` : use a single, imprecise base, for *all* allocations. Always converges.

The behavior of `-eva-alloc-builtin` is global, unless overridden by *allocation annotations*, described below.

Generally speaking, the safest approach is to start with the default builtin (`by_stack`), to ensure that the analysis will terminate. If the results are imprecise, and the allocation function is not called inside a loop, then the `fresh` variant may be tried. If you are mistaken, and the analysis starts diverging, it will print (by default) several messages of this form:

```
[eva] allocating variable __malloc_main_l42_2981
[eva] allocating variable __malloc_main_l42_2982
```

This indicates that new bases are being created. You must then manually interrupt the analysis and either unroll the loop entirely (see Section 6.4.1) or use a weak variant.

Dynamic allocation annotations The behavior of option `-eva-alloc-builtin` can be locally overridden via `eva_allocate` annotations preceding calls to dynamic allocation functions. For instance, the following annotation ensures that the call to `calloc` below will use the `fresh` builtin, regardless of the value of option `-eva-alloc-builtin`:

```
/*@ eva_allocate fresh; */
part = (char*)calloc(plen + 1, sizeof(*part));
```

Other calls to `calloc` will be unaffected by this annotation.

Multiple locations per callstack Option `-eva-mlevel` (default 0) sets the maximum number of calls to `malloc` (and similar functions) per call stack for which the weak version of the builtins will return a precise fresh location. Afterwards, the locations will be reused to ensure termination of the analysis – but leading to spurious aliasing and possible imprecision. In other words, setting `-eva-mlevel N` means that up to $N + 1$ different locations will be created for each call stack. This allows, for instance, loops with known bounds $\leq N$ to remain precise, while ensuring termination for other loops.

Memory allocation failure By default, stdlib-related memory allocation builtins in Eva (that is, `malloc`, `calloc` and `realloc`) consider that the allocation may fail, thus `NULL` is always returned as a possible value. To change this behavior (supposing that these functions never fail), use option `-eva-no-alloc-returns-null`.

Note that other allocation builtins, such as `__fc_vla_alloc` (for variable-length arrays) and `alloca`, *never* assume allocation fails.

9.2 Parameterizing the analysis

9.2.1 Adding non-determinism

The following functions, declared in `share/libc/__fc_builtin.h`, allow to introduce some non-determinism in the analysis. The results given by Eva are valid **for all values proposed by the user**, as opposed to what a test-generation tool would typically do. A tool based

on testing techniques would indeed necessarily pick only a subset of the billions of possible entries to execute the application.

```
int Frama_C_nondet(int a, int b);
    /* returns either a or b */

void *Frama_C_nondet_ptr(void *a, void *b);
    /* returns either a or b */

int Frama_C_interval(int min, int max);
    /* returns any value in the interval from min to max inclusive */

float Frama_C_float_interval(float min, float max);
    /* returns any value in the interval from min to max inclusive */

double Frama_C_double_interval(double min, double max);
    /* returns any value in the interval from min to max inclusive */
```

The implementation of these functions might change in future versions of Frama-C, but their types and their behavior will stay the same.

Example of use of the functions introducing non-determinism:

```
1 #include "__fc_builtin.h"
2
3 int A,B,X;
4 void main(void)
5 {
6   A = Frama_C_nondet(6, 15);
7   B = Frama_C_interval(-3, 10);
8   X = A * B;
9 }
```

With the command below, the obtained result for variable `X` is `[-45..150],0%3`.

```
frama-c -eva ex_nondet.c .../share/libc/__fc_builtin.c
```

The inclusion of `.../share/libc/__fc_builtin.c` is only required when using the functions `Frama_C_float_interval` and `Frama_C_double_interval`. Otherwise, including the file `__fc_builtin.h` is sufficient.

Note that reads of volatile variables also return a non-deterministic value.

9.3 Observing intermediate results

In addition to using the graphical user interface, it is also possible to obtain information about the value of variables at a particular point of the program in log files. This is done by inserting at the relevant points in the source code calls to the functions described below. These functions have no effect on the results of the analysis; in particular, no alarm is ever emitted on their calls, even when the evaluation of an argument could fail.

Currently, these functions all have an immediate effect, *i.e* they display the state that the analyzer is propagating at the time it reaches the call. Thus, these functions might expose some undocumented aspects of the behavior of the analyzer. This is especially visible when they are used together with semantic unrolling (see section 6.4.1). Displayed results may be counter-intuitive to the user. It is recommended to attach a greater importance to the union

of the values displayed during the whole analysis than to the particular order in which the subsets composing these unions are propagated by the analyzer.

9.3.1 Displaying the value of an expression

The values of some expressions `expr1`, `expr2...` during the analysis can be displayed with a call to the function `Frama_C_show_each_name(expr1, expr2...)`. They are displayed each time the analyzer reaches the call.

The place-holder "`_name`" can be removed or replaced by an arbitrary identifier. This identifier will appear in the output of the analyzer along with the value of the argument. Different identifiers can be used to differentiate each call of these functions, as shown in the following example:

```
void f(int x)
{
  int y;
  y = x;
  Frama_C_show_each(x);
  Frama_C_show_each_y(y);
  Frama_C_show_each_delta(y-x);
  ...
}
```

Potential alarms on the arguments of these functions (e.g. an overflow in the computation of `y-x`) are *not* emitted. This is by design.

9.3.2 Displaying the entire memory state

The memory states inferred at a program point can be displayed with a call to the function `Frama_C_dump_each()`. The current state is displayed each time the analyzer reaches the call.

The internal states of each additional domain described in Section 6.7 are also displayed if the domain's log category has been enabled through the option `-eva-msg-key category`, where `category` is the log category of the domain, shown in Figure 6.1.

9.3.3 Displaying internal properties about expressions

The internal properties inferred by each domain about some expressions `expr1`, `expr2...` can be displayed with a call to `Frama_C_domain_show_each(expr1, expr2...)`. They are displayed each time the analyzer reaches the call.

By default, only the internal representation of variables by the main domain (see Section 3.1) are shown. The properties inferred by each additional domain are also printed if the domain's log category has been enabled through the option `-eva-msg-key category`, where `category` is the log category of the domain, shown in Figure 6.1. The information printed by the additional domains is currently very limited.

9.4 Table of builtins

This table briefly summarizes all builtins present in Eva, with a short description of their behavior.

9.4.1 Floating-point operations

Generally speaking, all functions mentioned below are the counterpart of the standard library function of the same name, minus the `Frama_C_` prefix.

Floating-point builtins

`Frama_C_sqrt`	`Frama_C_pow`	`Frama_C_exp`	`Frama_C_log`
`Frama_C_log10`	`Frama_C_fmod`	`Frama_C_cos`	`Frama_C_sin`
`Frama_C_acos`	`Frama_C_asin`	`Frama_C_atan`	`Frama_C_atan2`
`Frama_C_ceil`	`Frama_C_floor`	`Frama_C_round`	`Frama_C_trunc`

Equivalent builtins exist for 32-bit float computations, with a name suffixed by `f`.

9.4.2 String operations

Builtins for functions of the `string.h` standard header.

String manipulation builtins

`Frama_C_memchr`	`Frama_C_rawmemchr`	`Frama_C_strchr`
`Frama_C_strlen`	`Frama_C_strnlen`	

Wide-character string manipulation builtins

`Frama_C_wmemchr`	`Frama_C_wcschr`	`Frama_C_wcslen`

`rawmemchr` *is a GNU extension to standard C.*

9.4.3 Memory manipulation

These builtins perform operations on the abstract memory. They correspond to the standard C library function of the same name.

Memory manipulation builtins

`Frama_C_memcpy`	`Frama_C_memset`	`Frama_C_memmove`

9.4.4 Dynamic allocation

These builtins are already described in section 5.6.4. They are listed here for completeness.

Dynamic memory allocation builtins

`Frama_C_malloc`	`Frama_C_alloca`	`Frama_C_vla_alloc`
`Frama_C_calloc`	`Frama_C_free`	`Frama_C_vla_free`
`Frama_C_realloc`		

9.4.5 Memory representation

These builtins allow to perform queries over the current abstract memory state.

- `Frama_C_is_base_aligned(p,n)` checks that the pointer argument `p` is aligned on `n` bytes, assuming that `\base_addr(p)` is itself aligned according to the alignment of its type (as defined by the current `machdep`).
- `Frama_C_offset(p)` returns the possible offsets of `p` with respect to its base address. That is, `Frama_C_offset(p) == \offset(p)` holds (but `Frama_C_offset(p)` can be used outside of ACSL fragments).

9.4.6 State-splitting builtins

The builtins below can be used to "split" abstract values in multiple separate intervals, as if a disjunction had been written (section 8.1.2). They take as first argument the expression on which to split, and as second argument the maximum admissible cardinality of the result, i.e. the maximum number of distinct abstract states that will be created. (See below.)

Splitting builtins

`Frama_C_builtin_split`	`Frama_C_builtin_split_pointer`	`Frama_C_builtin_split_all`

The builtins can only split on lvalues with pointer or integer type. The first argument of the three builtins must be an lvalue `l`, or a cast on a lvalue.

- `Frama_C_builtin_split` will split on the contents of `l` itself;
- `Frama_C_builtin_split_pointer` will split on the contents of `p` if `l` is of the form `*p`, `p->o` or `(*p)[i]`;
- `Frama_C_builtin_split_all` will split on all the lvalues present in `l`, including `l` itself, e.g. `i`, `q`, `*q`, `p` and `p->f[i][*q]` when called on `p->f[i][*q]`. Of course, this may create many states.

If the value(s) to split on has/have a greater cardinality than the second argument of the builtins, the split will not be performed. Note that sufficient `-slevel` (Section 6.4.1) must be available to propagate those states. The builtin will *not* be able to warn that all slevel has been consumed, and that the split will be inoperative. The second family of builtins can be used to compute the cardinality.

Cardinality builtins

`Frama_C_abstract_cardinal`	`Frama_C_abstract_min`	`Frama_C_abstract_max`

For example: `Frama_C_abstract_cardinal` returns `12` on `[6..36],0%3`, while `Frama_C_abstract_min` and `Frama_C_abstract_max` return `6` and `36` respectively.

Prototypes for those builtins can be found in `__fc_builtin.h`.

Chapter 10

FAQ

Well, for some value of "frequently"...

Q.1 Which option should I use to improve the handling of loops in my program?

Start with `-eva-auto-loop-unroll`. If automatic unrolling is not sufficient, the recommended way is to use `loop unroll` annotations on a case by case basis. This is the most precise and stable mechanism currently in Eva. It does have the drawback of requiring changes to the source code, however.

If none of the above techniques is suitable, using `-eva-slevel` is the next best approach. Compared to the previous ones, this option is more costly, often hard to predict, and can only be specified globally or at the function level (via `-eva-slevel-function`), however it works with loops that are built using gotos instead of `for` or `while`. It also improves precision when evaluating `if` or `switch` conditionals (but it is consumed by them, which can be confusing for the user).

Finally, there is an option from the Frama-C kernel, `-ulevel`, which performs a syntactic modification of the analyzed source code. Its advantage is that, by explicitly separating iteration steps, it allows using the graphical user interface to observe values or express properties for a specific iteration step of the loop. However, the duplication of loop statements and variables can clutter the code. Also, the transformation increases the size of the code in the Frama-C AST and, for large functions, this has a significant impact in the analysis time. For these reasons, `-ulevel` is seldom used nowadays.

Q.2 Alarms that occur after a true alarm in the analyzed code are not detected. Is that normal? May I give some information to the tool so that it detects those alarms?

The answers to these questions are "yes" and "yes". Consider the following example:

```
1  int x,y;
2  void main(void)
3  {
4    int *p=NULL;
5    x = *p;
6    y = x / 0;
7  }
```

When analyzing this example, Eva does not emit an alarm on line 6. This is perfectly correct, since no error occurs at run time on line 6. In fact, line 6 is not reached at all, since execution stops at line 5 when attempting to dereference the `NULL` pointer. It is unreasonable to expect Frama-C to perform a choice over what may happen after dereferencing `NULL`. It is possible to give some new information to the tool so that analysis can continue after a true alarm. This technique is called debugging. Once the issue has been corrected in the source code under analysis — more precisely, once the user has convinced themselves that there is no problem at this point in the source code — it becomes possible to trust the alarms that occur after the given point, or the absence thereof (see next question).

Q.3 Can I trust the alarms (or the absence of alarms) that occur after a false alarm in the analyzed code? May I give some information to the tool so that it detects these alarms?

The answers to these questions are respectively "yes" and "there is nothing special to do". If an alarm might be spurious, Eva automatically goes on. If the alarm is really a false alarm, the result given in the rest of the analysis can be considered with the same level of trust than if Frama-C had not displayed the false alarm. One should however keep in mind that this applies only in the case of a false alarm. Deciding whether the first alarm is a true or a false one is the responsibility of the user. This situation happens in the following example:

```
1  int x,y,z,r,i,t[101]={1,2,3};
2
3  void main(void)
4  {
5    x = Frama_C_interval(-10,10);
6    i = x * x;
7    y = t[i];
8    r = 7 / (y + 1);
9    z = 3 / y;
10 }
```

Analyzing this example with the default options produces:

```
[eva:alarm] false_al.c:7: Warning: accessing out of bounds index. assert 0 <= i;
[eva:alarm] false_al.c:9: Warning: division by zero. assert y != 0;
```

On line 7, the tool is only capable of detecting that `i` lies in the interval `-100..100`, which is approximated but correct. The alarm on line 7 is false, because the values that `i` can take at run-time lie in fact in the interval `0..100`. As it proceeds with the analysis, the plug-in detects that line 8 is safe, and that there is an alarm on line 9. These results must be interpreted thus: assuming that the array access on line 7 was legitimate, then line 8 is safe, and there is a threat on line 9. As a consequence, if the user can convince themselves that the threat on line 7 is false, they can trust these results (*i.e.* there is nothing to worry about on line 8, but line 9 needs further investigation).

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Bibliography

[BCF+] Patrick Baudin, Pascal Cuoq, Jean-Christophe Filliâtre, Claude Marché, Benjamin Monate, Yannick Moy, and Virgile Prevosto. June. Available at https://frama-c.com/download/acsl.pdf.

[CCK+] Loïc Correnson, Pascal Cuoq, Florent Kirchner, André Maroneze, Virgile Prevosto, Armand Puccetti, Julien Signoles, and Boris Yakobowski. *Frama-C User Manual*. CEA, List. Available at https://frama-c.com/download/frama-c-user-manual.pdf.

[JM09] Bertrand Jeannet and Antoine Miné. Apron: A library of numerical abstract domains for static analysis. In Ahmed Bouajjani and Oded Maler, editors, *Computer Aided Verification, 21st International Conference, CAV 2009, Grenoble, France, June 26 - July 2, 2009. Proceedings*, volume 5643 of *Lecture Notes in Computer Science*, pages 661–667. Springer, 2009.

[JPV18] Maxime Jacquemin, Sylvie Putot, and Franck Védrine. A reduced product of absolute and relative error bounds for floating-point analysis. In Andreas Podelski, editor, *Static Analysis - 25th International Symposium, SAS 2018, Freiburg, Germany, August 29-31, 2018, Proceedings*, volume 11002 of *Lecture Notes in Computer Science*, pages 223–242. Springer, 2018.

[RM07] Xavier Rival and Laurent Mauborgne. The trace partitioning abstract domain. *ACM Trans. Program. Lang. Syst.*, 29(5), August 2007.

[SAC+15] Julien Signoles, Thibaud Antignac, Loïc Correnson, Matthieu Lemerre, and Virgile Prevosto. *Frama-C Plug-in Development Guide*, February 2015. http://frama-c.com/download/frama-c-plugin-development-guide.pdf.

[Ven12] Arnaud Venet. The gauge domain: Scalable analysis of linear inequality invariants. In P. Madhusudan and Sanjit A. Seshia, editors, *Computer Aided Verification - 24th International Conference, CAV 2012, Berkeley, CA, USA, July 7-13, 2012 Proceedings*, volume 7358 of *Lecture Notes in Computer Science*, pages 139–154. Springer, 2012.

Appendix A

ACSL Quick Guide for Eva

Eva users are often required to read and write some amount of ACSL annotations: alarms generated by Eva, library function specifications, user assertions; all of these require some basic ACSL knowledge.

This quick guide should serve as a suitable introduction to ACSL specifications for Eva analyses, intended for complete ACSL beginners. It focuses on the specific subset of ACSL that is mostly useful for Eva, with some examples based on ACSL specifications from the Frama-C standard library.

For more details about the terms described here, and for the full ACSL reference documentation, consult [BCF+].

A.1 Basic Syntax

ACSL annotations are C comments; they are ignored by most tools, but parsed by the Frama-C kernel.

ACSL annotations begin with `//@` or `/*@`. No spaces are allowed before the '@'. Each single-line annotation (`//@`) is independent.

ACSL clauses *always* terminate with a semicolon (`;`) character. Multiline annotations are then closed with `*/`.

Function contracts are specified in a *single* annotation. This is *forbidden*:

```
//@ requires a != 0; // error: this annotation is not attached to the function
//@ ensures \result > 0;
int f(int a);
```

Function contracts with several clauses are equivalent to a logical **and** (&&) between them. E.g., `requires A; requires B;` is equivalent to `requires A && B;`.

You can use all C operators (bitwise, arithmetic, etc.) in ACSL expressions, **except** those with side-effects (e.g. `i++`).

Some mathematical Unicode characters are accepted: ∀, ℤ, ≥, etc. All have equivalent ASCII notations (`\forall`, `integer`, `>=`, etc).

Numbers are, by default, *mathematical integers*, of type `integer` (ℤ), or *real numbers*, of type `real` (ℝ). Casts can be used to convert them to C integers (`int`) or C floats (`double`).

Predefined ACSL symbols are often prefixed by a backslash to avoid name clashing (e.g. the `\valid` predicate contains a backslash to avoid shadowing a possible C identifier `valid`).

For Eva, the main ACSL operators which are *not* present in C are:

- *range* operator (`..`): specifies an interval in memory locations, e.g. `a[0 .. 7]` refers to all elements in `a` between 0 and 7, *included*. This means you should not forget adding a `-1` to many expressions when converting from C, i.e. `\valid(a[0 .. n-1])` for an array of `n` elements.
- *forall* and *implies* operators (`\forall` and `==>`): used in a few logical formulas; Eva currently only interprets some specific patterns when these operators are used. Also, note that most uses of `\forall` are subsumed by the *range* operator.

Note that the range operator can be used either with parentheses (when referring to pointers) or with brackets. Also remember that arithmetic operations with ranges follow the same rules of pointer arithmetics: the offsets depend on the pointer type. See Section A.11 for an example syntax when dealing with pointers to type `void`.

Special symbols ACSL annotations are preprocessed by default. This means you can use definitions such as `INT_MAX`, `EOF`, etc. For null pointers, the ACSL term `\null` can be used, notably if macro `NULL` is not available.

A.2 Kinds of clauses

The main kinds of clauses used by Eva are:

- assertions (`assert`): associated with *C statements* (in block scope, that is, non-global), you can think of them as some fancy version of the libc `assert` macro, defined in `assert.h`. They state properties which must hold at the program point where they are written.
- preconditions (`requires`): part of function contracts (can only be written before a function declaration), these clauses act as assertions placed before each function call.
- postconditions (`ensures`): also part of function contracts, Eva uses them to *reduce* the state after the call, that is, they improve precision of the analysis by discarding irrelevant states. Note that there are two modes: if Eva only has a specification for the function, then `ensures` are *considered valid*; if the function definition is also available, Eva will check the `ensures`. If it fails to prove them, it will generate alarms before reducing.
- assigns ... \from (`assigns`): also part of function contracts, they state all locations that are possibly modified by the function. For Eva, the `\from` part of these clauses also tells, in the case of pointers, where do the new values come from. Note that `assigns` means *possibly* modified; you should read them as "may assign".

Other clauses which are often used by Eva are function *behaviors*, for function contracts with multiple states. Inside behaviors, the *assumes* clause operates similarly to `requires`: it defines the behavior's preconditions.

Examples In the following code, we check that `malloc` did not return a null pointer:

```
int *p = malloc(4 * sizeof(int));
//@ assert p != \null;
```

If Eva was called with option `-eva-no-alloc-returns-null`, the assertion will be always true; otherwise, an alarm will be emitted, and only the states where `p` is non-null will continue.

Another example:

```
unsigned long long r = a << 32;
//@ assert r >= INT_MAX + 1 && r < LLONG_MAX;
```

Here, we see why ACSL numbers are mathematical integers by default; otherwise, the expression `INT_MAX + 1` might overflow, so we would need to use casts, making the expression harder to read and more error-prone.

Here is an example of a function annotation (some predicates will be detailed later):

```
/*@
   requires  \is_finite (x) && \valid(exp);
   ensures  \is_finite ( \result );
   ensures 0.5 <= \result < 1.0;
   assigns  \result , *exp \from x;
 */
double frexp(double x, int *exp);
```

This is a simplified version of the actual contract in Frama-C's standard library, in `math.h`. Function `frexp` converts a floating-point number (`x`) into a fractional part (the function result, between 0.5 and 1.0) and an exponent (`exp`). The specification can be read as follows, from top to bottom, and from left to right:

- `x` must be a finite floating-point value, that is, neither `inf`/`-inf` nor `NaN`;
- `exp` must point to a valid and writable memory location; in other words, assigning to `*exp` should be allowed;
- when the function returns, its result value will be finite;
- not only that, but the return value will be comprised between 0.5 (included) and 1.0 (excluded);
- the function may change the contents of the memory locations representing its result value (this is always the case for non-void functions) and `*exp` (hence why `exp` should point to a *writable* location).

For the real `frexp` function, many refinements are possible: to handle the case when `x` is zero, we can add a different *behavior*, in which the result is also zero. We can handle the cases when `x` is non-finite; we can improve the postcondition by giving the equivalent ACSL formula that establishes the mathematical relation between `x`, `*exp` and `\result`; etc.

A.3 Useful ACSL predicates

An ACSL *predicate* is a function returning a boolean value. Predicates are used as part of expressions, so they are often preceded by a backslash. By convention, *builtin* ACSL predicates start with a backslash, but *user-defined* ACSL predicates are not.

The following predicates are abundantly used by Eva:

- `\valid(<locations>)`: expresses the fact that the given <locations> can be *written* to; **note**: it is a common mistake to use `\valid` when `\valid_read` is intended (see below);
- `\valid_read(<locations>)`: the given locations can be *read*, e.g. they point to a string literal, or to a location containing memory properly allocated and not yet freed;
- `\initialized(<locations>)`: the given locations have a properly initialized value; this does not hold, for instance, for a freshly malloc'ed block, or for uninitialized local variables.

Examples A simplified version of the `strcat` specification in Frama-C's libc is presented below. As a reminder, `strcat(d, s)` appends the string `s` at the end of string `d`.

```
/*@ requires valid_read_string(src);
  @ requires valid_read_string(dest);
  @ requires \valid(dest+(strlen(dest)..strlen(dest)+strlen(src)));
  @ ensures \result == dest;
  @ assigns dest[strlen(dest)..strlen(dest)+strlen(src)]
  @     \from src[0..strlen(src)];
  @ assigns \result \from dest;
  @*/
char *strcat(char *dest, const char *src);
```

Let us read this specification carefully:

- the string to be copied (`src`) must be a valid string, that is, readable and nul-terminated;
- the destination string must *also* be a valid string (since we are copying *after* this string, we need to know where it ends);
- there must be enough room, in the buffer pointed to by `dest`, *after* the length of `dest` itself, to store each of the characters of `src`, including the terminating zero character; this is described via the `\valid` predicate, which imposes writability of its memory locations, and via a range operator, which avoids having to use a `\forall` operator;
- the postcondition is trivial: it simply returns the destination pointer, unchanged;
- there are two `assigns` clauses, because their `\from` clauses are distinct. The first one states that the function may modify the memory at all locations between the end of the `dest` string (including its terminating zero character, which is located at `dest[strlen(dest)]`) and `dest[strlen(dest)+strlen(src)]`, which is the end of the newly-concatenated string. The second `assigns` clause simply states that the result value comes from the pointer `dest`. This clause is essential, otherwise the postcondition `\result == dest` cannot hold: in Eva, pointer values coming from specifications must be included in the locations indicated by a `\from` clause.

Note that the specification above is missing some important points: first, we never specify that the bytes in the range `dest[strlen(dest)`0..strlen(src)] are identical to those in `src[0..strlen(src)]`. Second, we omitted the fact that `src` and `dest` must be *disjoint*: `strcat` does not accept overlapping bytes between source and destination. In ACSL, this is specified via the `\separated(<locations>)` predicate (see below). This predicate is essential for WP, but in Eva it is present much less often. Third, we never stated that all of the modified

bytes were *actually* modified, that is: we are *certain* that their locations have been written to, and are thus considered `\initialized`.

Finally, here is an example using the `\initialized` predicate:

```
volatile time_t __fc_time;

/*@
  requires \valid(timer);
  assigns *timer \from __fc_time;
  ensures \initialized(timer);
*/
void time(time_t *timer);
```

This is a simple version of the libc's `time` function, which initializes the `timer` pointer with the value of the current system time (here, modeled by the global variable `__fc_time`).

The important point to notice is that, if we omit the `ensures` clause, the value of `timer` after the call will always include "or UNINITIALIZED", leading to an alarm before its use.

A.4 (Optional) Other useful predicates

We present here a few more useful predicates, for reference. These are sometimes present in the Frama-C standard library specifications.

\separated

The `\separated(<locations>)` predicate states that a set of locations are *disjoint*, or *non-overlapping*, similar to the `restrict` qualifier in C.

Example The `strncpy` function requires source and destination to be non-overlapping. For a call to `strncpy(d, s, n)`, this can be written as:

```
\separated(d + (0 .. n-1), s + (0 .. n-1));
```

Note that range operators are used to ensure that *all* bytes are non-overlapping; `\separated(d, s)` would have been incorrect, since it only considers the first byte in each string.

\subset as Eva-friendly alternative to \exists

The `\subset(elem, set)` predicate is an "Eva-friendly" alternative to the existential quantifier, `\exists`. Eva is often able to handle the former, but rarely the latter.

Example The C library function `strtod(p, *endp)` parses a floating-point number in string form (at `p`), returns it as a `double`, and (optionally) stores the pointer to the string *after* the conversion in `endp`. As written in the Linux Programmer's Manual:

> A pointer to the character after the last character used in the conversion is stored in the location referenced by `endptr`.

Therefore, we know that `*endptr` is *somewhere* inside the `ptr` buffer. In ACSL, we can write this as:

```
ensures \subset(*endptr, ptr+(0..));
```

This style of writing allows Eva to reduce the values of `*endptr`, avoiding the creation of *garbled mix*.

A.5 Behaviors

Most C functions, especially those in the C standard library, have at least two distinct paths: the "success" path and the "failure" path. Allocating memory, reading a file, writing to a device, performing a complex operation... all of these may fail. Specifications for such functions may become very imprecise ("everything may happen, therefore any return value is possible"), or rely on too many logical implications (e.g. `ensures p != \null ==> \result == 0 && p == \null ==> \result != 0;`). To help deal with such cases, ACSL has function *behaviors*, which allow splitting such sets of states, as in the following example of a floating-point `abs` (absolute value) function:

```
/*@
  assigns \result \from x;
  behavior normal:
    assumes finite_arg: \is_finite(x);
    ensures res_finite: \is_finite(\result);
    ensures positive_result: \result >= 0.;
    ensures equal_magnitude_result: \result == x || \result == -x;
  behavior infinity:
    assumes infinite_arg: \is_infinite(x);
    ensures infinite_result: \is_plus_infinity(\result);
  behavior nan:
    assumes nan_arg: \is_NaN(x);
    ensures nan_result: \is_NaN(\result);
  complete behaviors;
  disjoint behaviors;
*/
double fabs(double x);
```

This is (or was) the actual, full specification of the function in Frama-C's standard library. It contains 3 behaviors, separated according to the finiteness of the input value: finite, infinite, or NaN (*not a number*).

Each behavior has a named[1] *assumes* clause, which is the precondition for that behavior to be *active*. ACSL allows several behaviors to be active at the same time, but in practice, having disjoint behaviors (at most one single behavior active at any time) simplifies reasoning. When behaviors are disjoint, the union of two `assumes` clauses is always empty.

Ideally, behaviors should be *complete*: at least one of them should be active at any time[2]. Incomplete behaviors may lead to loss of precision.

Note that several ACSL floating-point predicates are used: `\is_finite`, `\is_infinite`, `\is_plus_infinity` and `\is_NaN`. They are explained in Section A.6.

[1] Named predicates are an ACSL feature; names, or *ids*, are described in Section A.9, *ACSL ids*.

[2] Hence, as is the case here, a complete and disjoint set of behaviors means that exactly one behavior is active at any time

(Optional) Assigns clauses in behaviors One of the major pain points of ACSL behaviors (besides the size of the specification, in number of lines) is the `assigns` clause: they must have a "default" clause (one that is outside any behaviors) that is a superset of the `assigns` clauses of each behavior. For instance, if a behavior `a` has a clause `assigns p;` and a behavior `b` has a clause `assigns q;`, then the default `assigns` clause must contain (at least) `assigns p, q;`.

The above fact leads to seemingly redundant clauses in some specifications, but they are in fact needed.

A.6 Floating-point

Floating-point specifications in ACSL contain *several* caveats. Historically, Eva supported only *finite* floating-point numbers, thus requiring all specifications to include clauses such as `requires \is_finite(x);`.

Nowadays, with 3 different modes related to non-finite[3] floating-point values (defined by option `-warn-special-float`: `none`, `nan` and `non-finite`), specifications for functions in `math.h` usually should cover all three cases.

By default, relational comparison operators are based on *real* numbers, not floating-point; many specifications require instead the use of predicates such as `gt_double` and `lt_float`.

Due to such complications, several expressions result in unintuitive behaviors; for instance, some specifications require an `ensures \is_finite(\result);` before a more specific ensures, such as `ensures \result >= 0.0;`, otherwise Eva is unable to reduce the interval, due to the presence of NaNs.

For more complex examples using floats, take a look at the specifications in `math.h`, from the Frama-C standard library.

A.7 Dynamic memory allocation

ACSL has several elements to handle dynamic memory allocation: clauses `allocates` and `frees`, as well as the `\fresh` predicate. Currently, Eva does *not* interpret these elements. Instead, Eva has a set of builtins and options to handle functions such as `malloc`, `free`, `realloc`, `alloca` (non-standard), etc. These functions are handled in a special way; their ACSL specifications are not currently used by Eva.

Some POSIX functions, such as `strdup`, perform memory allocation and contain `allocates` clauses. Currently, Eva whitelists the functions for which there are *implementations* in the Frama-C standard library, to ensure Eva handles them correctly. If you want to use a function that allocates or frees dynamic memory, you will need to write it in C code[4], not in ACSL.

A.8 Logic versus C

In ACSL, there is a "higher level of abstraction" that sits above the level of C constructs: the logic level. In many cases, it can be abstracted away, but it is important to remember that it exists.

[3] The distinction between *non-finite* and *infinite* (or *infinity*) is subtle: *non-finite* includes *both* positive and negative infinities, as well as NaNs; *infinite* only includes infinities. Hence why ACSL contains so many predicates. The negation of `\is_finite` is *not* `\is_infinite`!

[4] It suffices to write an abstract version of the code, using e.g. Frama-C builtins such as `Frama_C_interval`.

For instance, numbers (integers and reals) are almost always at the logic level, where there are no overflows and no rounding errors. Conversely, there are neither floating-point infinities nor NaNs. Take this into account when specifying mathematical functions.

There are also logic identifiers which may resemble C library functions (e.g. `strlen`, `memcmp`, `pow`), but are defined as *logic functions*. We do not detail logic functions in this guide; just remember that, whenever you see a function name in ACSL, it *always* refers to a logic function; it is not possible to call a C function in an ACSL annotation.

A.9 (Optional) Syntax Complements

We present here a few more details about ACSL syntax; you may skip this until you are more familiar with the rest of the guide.

Empty and unbounded ranges

A range `l .. u` where $l > u$ is an *empty* range; in some specifications, this can happen due to variable bounds (e.g. `a[0..n-1]` when `n` is 0).

The bounds of the range operator (`l .. u`) are optional: you can write `b[0 ..]`, `b[.. 2]`, or even `b[..]`. A missing left bound means "negative infinity", and a missing right bound means "positive infinity". For instance, `assigns b[0..]` is useful when the upper bound is unknown.

Range tokenization: add spaces between bounds

An unfortunate combination of preprocessing and parsing of logical annotations can lead to unexpected parsing errors. Consider the following code using a range operator:

```
#define N 10
int main(void) {
  int a[N] = {0};
  //@ assert 0 \in a[0..N-1];
}
```

Parsing the above code fails with `[kernel:annot-error] unbound logic variable N`. The issue is that, according to the C standard, `0..N` is a preprocessing token in itself, so that the preprocessor does not see `N` in isolation, and does not expand the macro. To fix this, simply add spaces between the bounds: `a[0 .. N-1]`. As a general rule, we recommend *always* adding spaces between the bounds.

ACSL ids

Most ACSL constructs can have one or more *ids*, or *names*, which are C-like identifiers suffixed by a colon (`:`). Some have a semantic impact (e.g., `indirect` in `from` clauses, as seen in Section A.10), but they are mostly used as clause identifiers: either to provide some sort of description, or to help when pretty-printing. When a clause has names, they are used instead of printing the whole predicate.

You can add several names by juxtaposing them, e.g.:

```
  ensures exp_ok: initialization: \initialized(exp);
```

The above clause has two names: `exp_ok` and `initialization`.

Names are not required to be unique. Uniqueness is never checked.

A.10 Remarks concerning Eva

This section lists some uses and limitations of ACSL annotations that are specific to the Eva plugin.

Indirect 'from' clauses

Section 8.2 explains the difference between direct and indirect `\from` clauses. In a very briefly manner, `indirect` `\from`s are more precise, but may result in unsound analyses, if the source location contains pointers (or parts of pointers).

As a general rule of thumb, if you obtain garbled mix in non-pointer variables, in cases where that would have no practical sense, consider adding `indirect:` labels to `\from` clauses. The Frama-C libc can be a source of inspiration.

Disjunctions versus intervals

In some cases, Eva can obtain more precision from the use of explicit disjunctions instead of non-contiguous intervals. The canonical example is the suppression of a 0 from the middle of a interval; instead of writing this:

```
ensures nonzero_result: \result != 0;
```

It is often preferable to write this:

```
ensures nonzero_result: \result > 0 || \result < 0;
```

In the first case, unless the sign domain (option `-eva-domains sign`) is enabled, there is little chance that Eva will produce an interval without zero.

In the second case, if there is enough slevel (or some other disjunction mechanism is enabled), Eva will produce two separate states: one with `\result > 0` and another with `\result < 0`, at least until both states have to be merged later.

Separate behaviors also enable this kind of disjunctive reasoning.

A.11 FAQ / Troubleshooting / Common errors

This section lists some common error messages, and how to fix them.

Error: cannot use a pointer to void here. Pointer arithmetics in ACSL require non-void pointers. For instance, in the `memcpy` function, which accepts `void` pointers (instead of `char` pointers), the following is invalid:

```
assigns dest[0..n - 1] \from src[0..n-1];
```

You need to explicitly cast the pointers to `char*`, as in:

```
assigns ((char*)dest)[0..n - 1] \from ((char*)src)[0..n-1];
```

Completely invalid destination for assigns clause <A>. Ignoring. This is not an error *per se*, but often associated with an incorrect `assigns` clause (e.g. a missing `&`). The most common legitimate occurrence of this message is when a function has an optional outgoing parameter (i.e., "if `old` is non-NULL, the previous value is saved in `old`") and has been called with a null pointer. In this case, the message can be safely ignored.