

Secure Your Things: Secure Development of IoT Software with Frama-C

Tutorial at IEEE SecDev 2018

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Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP

Runtime Verification using E-ACSL

Conclusion

And Security?

By Waqas on October 23, 2016 [Email](#) [@hackmad](#) [CIBERATTACKS](#) [HEALTH](#) [SECURITY](#)



ANDY GREENBERG SECURITY 07.21.15 06:00 AM

HACKERS REMOTELY KILL A JEEP ON THE HIGHWAY—WITH ME IN IT



by Tom Spring

August 26, 2016, 2:55 pm

Hacking a computer-aided sniper rifle

Elizabeth Weise | USATODAY

Published 5:56 p.m. UTC Aug 7, 2015

Outline

Introduction

Security in the IoT

An overview of Frama-C

The Contiki operating system

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Frama-C Historical Context

- ▶ 90's: [CAVEAT](#), Hoare logic-based tool for C code at CEA
- ▶ 2000's: [CAVEAT used by Airbus](#) during certification process of the A380 (DO-178 level A qualification)
- ▶ 2002: [Why](#) and its C front-end [Caduceus](#) (at INRIA)
- ▶ 2004: start of Frama-C project as a successor to CAVEAT and Caduceus
- ▶ 2008: [First public release](#) of Frama-C (Hydrogen)
- ▶ 2012: [WP](#): Weakest-precondition based plugin
- ▶ 2012: [E-ACSL](#): Runtime Verification plugin
- ▶ 2013: CEA Spin-off [TrustInSoft](#)
- ▶ 2016: [Eva](#): Evolved Value Analysis
- ▶ 2016: [Frama-Clang](#): C++ extension
- ▶ 2017: [Frama-C Sulfur](#) (v.16)
- ▶ Today: [Frama-C Chlorine](#) (v.17)

Frama-C Open-Source Distribution

Framework for Analysis of source code written in ISO 99 C
[Kirchner et al, FAC'15]

- ▶ analysis of C code extended with **ACSL** annotations
- ▶ ACSL Specification Language
 - ▶ *lingua franca* of Frama-C analyzers
- ▶ mostly **open-source** (LGPL 2.1)

<http://frama-c.com>
- ▶ also proprietary extensions and distributions
- ▶ targets both **academic** and **industrial** usage



Example: a C Program Annotated in ACSL

```

/*@ requires n>=0 && \valid(t+(0..n-1));
   assigns \nothing;
   ensures \result != 0 <==>
      (\forall integer j; 0 <= j < n ==> t[j] == 0);
*/
int all_zeros(int t[], int n) {
  int k;
  /*@ loop invariant 0 <= k <= n;
     loop invariant \forall integer j; 0<=j<k ==> t[j]==0;
     loop assigns k;
     loop variant n-k;
  */
  for(k = 0; k < n; k++)
    if (t[k] != 0)
      return 0;
  return 1;
}

```

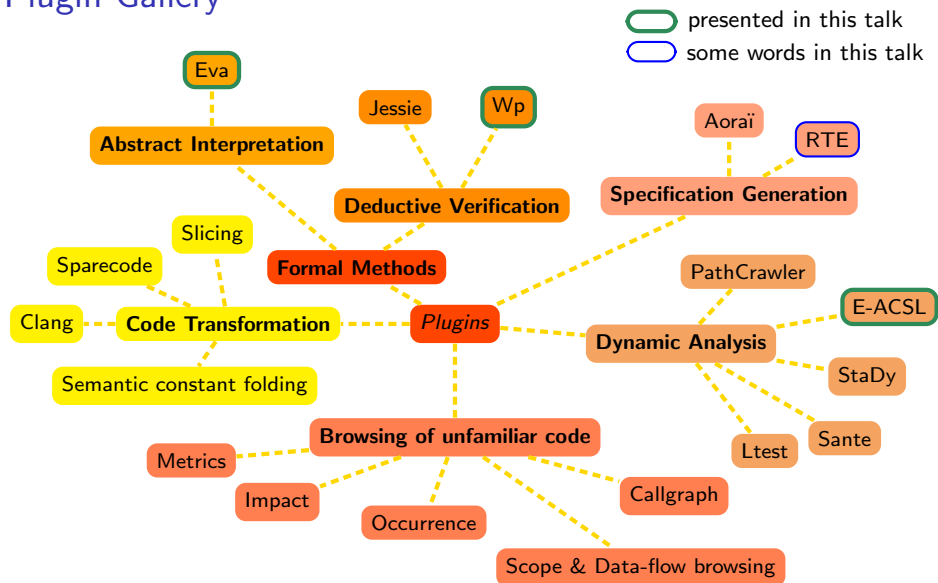
Can be proven
with Frama-C/WP

Frama-C, a Collection of Tools

Several tools inside a single platform

- ▶ **plugin architecture** like in Eclipse
- ▶ tools provided as plugins
 - ▶ over 20 plugins in the open-source distribution
 - ▶ close-source plugins, either at CEA (about 20) or outside
- ▶ a common **kernel**
 - ▶ provides a uniform setting
 - ▶ provides general services
 - ▶ synthesizes useful information

Plugin Gallery



Frama-C, a Development Platform

- ▶ mostly developed in **OCaml** (\approx 180 kloc in the open-source distribution, \approx 300 kloc with proprietary extensions)
- ▶ initially based on **Cil** [Necula et al, CC'02]
- ▶ **library** dedicated to analysis of C code

development of plugins by third party

- ▶ dedicated plugins for **specific task** (verifying your coding rules)
- ▶ dedicated plugins for fine-grained parameterization
- ▶ **extensions** of existing analysers

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A lightweight OS for IoT

Contiki is a lightweight operating system for IoT

It provides a lot of features (for a micro-kernel):

- ▶ (rudimentary) memory and process management
- ▶ networking stack and cryptographic functions
- ▶ ...

Typical hardware platform:

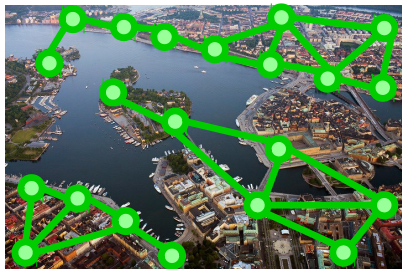
- ▶ 8, 16, or 32-bit MCU (little or big-endian),
- ▶ low-power radio, some sensors and actuators, ...

Note for security: **there is *no* memory protection unit.**



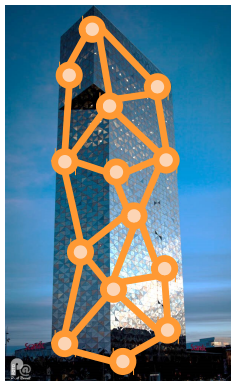
Contiki: Typical Applications

- ▶ **IoT scenarios:** smart cities, building automation, ...
- ▶ Multiple hops to cover large areas
- ▶ **Low-power** for battery-powered scenarios
- ▶ Nodes are interoperable and addressable (IP)



*Traffic lights
Parking spots
Public transport
Street lights
Smart metering
...*

*Light bulbs
Thermostat
Power sockets
CO2 sensors
Door locks
Smoke detectors
...*



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Value Analysis Overview

Compute possible values of variables at each program point

- ▶ an automatic analysis
- ▶ based on **abstract interpretation**
- ▶ produces a correct over-approximation
- ▶ reports **alarms** for potentially invalid operations
- ▶ reports alarms for potentially invalid ACSL annotations
- ▶ **can prove the absence of runtime errors**
- ▶ **graphical interface**: displays the domains of each variable

Domains of Value Analysis

▶ Historical domains

- ▶ **small sets** of integers, e.g. $\{5, 18, 42\}$
- ▶ reduced product of **intervals**: quick to compute, e.g. $[1..41]$
- ▶ **modulo**: pretty good for arrays of structures, e.g. $[1..41], 1\%2$
- ▶ precise representation of **pointers**, e.g. *32-bit aligned offset from $\&t[0]$*
- ▶ **initialization** information

▶ Eva, Evolved Value Analysis

- ▶ more **generic and extensible** domains
- ▶ possible to add new, or combine domains

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Example 1

Run Eva: `frama-c-gui div1.c -val -main=f`

```
int f ( int a ) {  
  int x, y;  
  int sum, result;  
  if(a == 0){  
    x = 0; y = 0;  
  }else{  
    x = 5; y = 5;  
  }  
  sum = x + y; // sum can be 0  
  result = 10/sum; // risk of division by 0  
  return result;  
}
```

Risk of division by 0 is detected, it is real.

Example 2

Run Eva: `frama-c-gui div2.c -val -main=f`

```
int f ( int a ) {  
    int x, y;  
    int sum, result;  
    if(a == 0){  
        x = 0; y = 5;  
    }else{  
        x = 5; y = 0;  
    }  
    sum = x + y; // sum cannot be 0  
    result = 10/sum; // no div. by 0  
    return result;  
}
```

Risk of division by 0 is detected, but it is a false alarm.

Eva Parameterization

- ▶ Eva is **automatic**, but can be imprecise due to **overapproximation**
- ▶ a **fine-tuned parameterization** for a **trade-off** precision / efficiency
- ▶ One useful option: **slevel n**
 - ▶ keep up to $n + 1$ states in parallel during the analysis
 - ▶ different slevel's can be set for specific functions or loops

Example 2, cont'd

Run Eva: `frama-c-gui div2.c -val -main=f -slevel 2`

```
int f ( int a ) {  
  int x, y;  
  int sum, result;  
  if(a == 0){  
    x = 0; y = 5;  
  }else{  
    x = 5; y = 0;  
  }  
  sum = x + y; // sum cannot be 0  
  result = 10/sum; // no div. by 0  
  return result;  
}
```

Absence of division by 0 is proved, no false alarm.

Example 3

Run Eva: `frama-c-gui div3.c -val -main=f`

```
int f ( int a ) {  
  int x, y;  
  int sum, result;  
  if(a == 0){  
    x = 0; //y = 5;  
  }else{  
    x = 5; y = 0;  
  }  
  sum = x + y; // y can be non-initialized  
  result = 10/sum;  
  return result;  
}
```

Alarm on initialization of `y` is reported.

Example 3, cont'd

Run Eva: `frama-c-gui div3.c -val -main=f -slevel 2`

```
int f ( int a ) {  
    int x, y;  
    int sum, result;  
    if(a == 0){  
        x = 0; //y = 5;  
    }else{  
        x = 5; y = 0;  
    }  
    sum = x + y; // y can be non-initialized  
    result = 10/sum;  
    return result;  
}
```

Alarm on initialization of `y` is reported, even with a bigger level

Example 4

Run Eva: `frama-c-gui sqrt.c -val`

```
#include " _fc_builtin.h"
int A, B;
int root(int N){
    int R = 0;
    while(((R+1)*(R+1)) <= N) {
        R = R + 1;
    }
    return R;
}

void main(void)
{
    A = Frama_C_interval(0,64);
    B = root(A);
}
```

Risk of arithmetic overflows is reported

Example 4, cont'd

Run Eva: `frama-c-gui sqrt.c -val -slevel 8`

```
#include " _fc_builtin.h"
int A, B;
int root(int N){
    int R = 0;
    while(((R+1)*(R+1)) <= N) {
        R = R + 1;
    }
    return R;
}

void main(void)
{
    A = Frama_C_interval(0,64);
    B = root(A);
}
```

Absence of overflows is proved with a bigger slevel

Example 5

Run Eva: `frama-c-gui pointer1.c -val`

```
#include "stdlib.h"

int main(void){
  int *p;
  if( p )
    *p = 10;
  return 0;
}
```

Alarm on initialization of `p` is reported

Example 6

Run Eva: `frama-c-gui pointer2.c -val`

```
#include "stdlib.h"

int main(void){
  int * p = (int*)malloc(sizeof(int));
  *p = 10;
  return 0;
}
```

Alarm on validity of `p` is reported

Example 7

Run Eva: `frama-c-gui pointer3.c -val`

```
#include "stdlib.h"

int main(void){
  int * p = (int*)malloc(sizeof(int));
  if( p )
    *p = 10;
  return 0;
}
```

Absence of runtime errors is proved

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Overview of the aes-ccm Modules

- ▶ **Critical!** – Used for communication security
 - ▶ end-to-end confidentiality and integrity
- ▶ **Advanced Encryption Standard (AES)**: a symmetric encryption algo.
 - ▶ AES replaced in 2002 Data Encryption Standard (DES)
- ▶ **Modular API** – independent from the OS
- ▶ Two modules:
 - ▶ AES-128
 - ▶ AES-CCM* block cypher mode
 - ▶ A few hundreds of LoC
- ▶ **High complexity crypto code**
 - ▶ Intensive integer arithmetics
 - ▶ Intricate indexing
 - ▶ based on multiplication over finite field $GF(2^8)$

Examples 8, 9, 10

Analyze three versions of a part of the aes module

Explore and explain the results

Ex.8. Run Eva: `frama-c-gui aes1.c -val`

Ex.9. Run Eva: `frama-c-gui aes2.c -val`

Ex.10. Run Eva: `frama-c-gui aes3.c -val`

Examples 11, 12, 13, 14

Analyze three versions of a part of the `ccm` module

Explore and explain the results

Ex.11. Run Eva: `frama-c-gui ccm1.c -val`

Ex.12. Run Eva: `frama-c-gui ccm1.c -val -slevel 50`

Ex.13. Run Eva: `frama-c-gui ccm2.c -val -slevel 50`

Ex.14. Run Eva: `frama-c-gui ccm3.c -val -slevel 50`

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- Overview of ACSL and WP

- Function contracts

- Programs with loops

- An application to Contiki

- My proof fails... What to do?

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Objectives of Deductive Verification

Rigorous, mathematical proof of semantic properties of a program

- ▶ functional properties
- ▶ safety:
 - ▶ all memory accesses are valid,
 - ▶ no arithmetic overflow,
 - ▶ no division by zero, ...
- ▶ termination

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ACSL: ANSI/ISO C Specification Language

Presentation

- ▶ Based on the notion of **contract**, like in Eiffel, JML
- ▶ Allows users to specify **functional properties** of programs
- ▶ Allows **communication** between various plugins
- ▶ **Independent** from a particular analysis
- ▶ Manual at <http://frama-c.com/acsl>

Basic Components

- ▶ Typed first-order logic
- ▶ Pure C expressions
- ▶ C types + \mathbb{Z} (integer) and \mathbb{R} (real)
- ▶ Built-ins predicates and logic functions, particularly over pointers:
`\valid(p)`, **`\valid(p+0..2)`**, **`\separated(p+0..2,q+0..5)`**,
`\block_length(p)`

WP plugin

- ▶ Hoare-logic based plugin, developed at CEA List
- ▶ Proof of semantic properties of the program
- ▶ Modular verification (function by function)
- ▶ Input: a program and its specification in ACSL
- ▶ WP generates verification conditions (VCs)
- ▶ Relies on Automatic Theorem Provers to discharge the VCs
 - ▶ Alt-Ergo, Z3, CVC3, CVC4, Yices, Simplify ...
- ▶ WP manual at <http://frama-c.com/wp.html>
- ▶ If all VCs are proved, the program respects the given specification
 - ▶ Does it mean that the program is correct?
 - ▶ NO! If the specification is wrong, the program can be wrong!

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Contracts

- ▶ **Goal:** specification of imperative functions
- ▶ **Approach:** give assertions (i.e. properties) about the functions
 - ▶ **Precondition** is supposed to be true on entry (ensured by the caller)
 - ▶ **Postcondition** must be true on exit (ensured by the function)
- ▶ Nothing is guaranteed when the precondition is not satisfied
- ▶ **Termination** may be guaranteed or not (total or partial correctness)

Primary role of contracts

- ▶ Must reflect the informal specification
- ▶ Should not be modified just to suit the verification tasks

Example 1

Specify and prove the following program:

```
// returns the absolute value of x  
int abs ( int x ) {  
  if ( x >=0 )  
    return x ;  
  return -x ;  
}
```

Try to prove with Frama-C/WP using the basic command

▶ `frama-c-gui -wp file.c`

Example 1 (Continued)

Run WP: `frama-c-gui -wp 01-abs-1.c`

The basic proof succeeds for the following program:

```

/*@ ensures (x >= 0 ==> \result == x) &&
    (x < 0 ==> \result == -x);
*/
int abs ( int x ) {
    if ( x >=0 )
        return x ;
    return -x ;
}

```

- ▶ The returned value is not always as expected.
- ▶ For $x = \text{INT_MIN}$, $-x$ cannot be represented by an `int` and overflows
- ▶ Example: on 32-bit, $\text{INT_MIN} = -2^{31}$ while $\text{INT_MAX} = 2^{31} - 1$
- ▶ Run WP: `frama-c-gui -wp -wp-rte 01-abs-1.c`

Safety warnings: arithmetic overflows

Absence of arithmetic overflows can be important to check

- ▶ A sad example: crash of Ariane 5 in 1996

WP can automatically check the absence of runtime errors

- ▶ Use the command `frama-c-gui -wp -wp-rte file.c`
- ▶ It generates VCs to ensure that runtime errors do not occur
 - ▶ in particular, arithmetic operations do not overflow
- ▶ If not proved, an error may occur.

Example 1 (Continued) - Solution

Run WP: `frama-c-gui -wp -wp-rte 01-abs-2.c`

This completely specified program is proved:

```

#include <limits.h>
/*@ requires x > INT_MIN;
    ensures (x >= 0 ==> \result == x) &&
           (x < 0 ==> \result == -x);
    assigns \nothing;
*/
int abs ( int x ) {
    if ( x >= 0 )
        return x ;
    return -x ;
}

```

Example 2

Specify and prove the following program:

```
// returns the maximum of a and b  
int max ( int a, int b ) {  
  if ( a > b )  
    return a ;  
  return b ;  
}
```

Example 2 (Continued) - Find the error

Run WP: `frama-c-gui -wp -wp-rte 02-max-1.c`

The following program is proved. Do you see any error?

```
/*@ ensures \result >= a && \result >= b;  
*/  
int max ( int a, int b ) {  
  if ( a >= b )  
    return a ;  
  return b ;  
}
```

Example 2 (Continued) - A wrong version

Run WP: `frama-c-gui -wp -wp-rte 02-max-2.c`

This is a wrong implementation that is also proved. Why?

```
#include<limits.h>
/*@ ensures \bresult >= a && \bresult >= b; */
int max ( int a, int b ) {
    return INT_MAX ;
}
```

- ▶ Our specification is incomplete
- ▶ Should say that the returned value is one of the arguments

Example 2 (Continued) - Another issue

The following program is proved. Do you see any issue?

```
/*@ ensures \result >= a && \result >= b;  
    ensures \result == a || \result == b ;  
*/  
int max ( int a, int b ) {  
    if ( a >= b )  
        return a ;  
    return b ;  
}
```


Example 2 (Continued) - Another issue

Run WP: `frama-c-gui -wp -wp-rte 02-max-3.c`

With this specification, we cannot prove the following program. Why?

```

/*@ ensures \result >= a && \result >= b ;
    ensures \result == a || \result == b ; */
int max(int a, int b);

extern int v ;

int main(){
  v = 3;
  int r = max(4,2);
  //@ assert v == 3 ;
}

```

- ▶ Again, our specification is incomplete
- ▶ Should say that max does not modify any memory location

Assigns clause

The clause **assigns** v_1, v_2, \dots, v_N ;

- ▶ Part of the postcondition
- ▶ Specifies which (non local) variables can be modified by the function
- ▶ If nothing can be modified, specify **assigns \nothing**

Example 2 (Continued) - Solution

Run WP: `frama-c-gui -wp -wp-rte 02-max-4.c`

This completely specified program is proved:

```
/*@ ensures \result >= a && \result >= b;  
    ensures \result == a || \result == b;  
    assigns \nothing;  
*/  
int max ( int a, int b ) {  
    if ( a >= b )  
        return a ;  
    return b ;  
}
```

Example 3

Specify and prove the following program:

```
// returns the maximum of *p and *q  
int max_ptr ( int *p, int *q ) {  
  if ( *p >= *q )  
    return *p ;  
  return *q ;  
}
```

Example 3 (Continued) - A proof failure

Run WP: `frama-c-gui -wp -wp-rte 03-max_ptr-1.c`

Explain the proof failure for the program:

```
/*@ ensures \result >= *p && \result >= *q;  
    ensures \result == *p || \result == *q;  
*/  
int max_ptr ( int *p, int *q ) {  
    if ( *p >= *q )  
        return *p ;  
    return *q ;  
}
```

- ▶ Nothing ensures that pointers p , q are valid
- ▶ It must be ensured either by the function, or by its precondition

Safety warnings: invalid memory accesses

An invalid pointer or array access may result in a **segmentation fault or memory corruption**.

- ▶ WP can automatically generate VCs to check memory access validity
 - ▶ use the command `frama-c-gui -wp -wp-rte file.c`
- ▶ They ensure that each pointer (array) access has a **valid offset (index)**
- ▶ If the function assumes that an input pointer is valid, it must be **stated in its precondition**, e.g.
 - ▶ `\valid(p)` for one pointer `p`
 - ▶ `\valid(p+0..2)` for a range of offsets `p`, `p+1`, `p+2`

Example 3 (Continued) - Another issue

Run WP: `frama-c-gui -wp -wp-rte 03-max_ptr-2.c`

The following program is proved. Do you see any issue?

```
/*@ requires \valid(p) && \valid(q);
    ensures \result >= *p && \result >= *q;
    ensures \result == *p || \result == *q;
*/
int max_ptr ( int *p, int *q ) {
    if ( *p >= *q )
        return *p ;
    return *q ;
}
```

Example 3 (Continued) - A wrong version

Run WP: `frama-c-gui -wp -wp-rte 03-max_ptr-3.c`

This is a wrong implementation that is also proved. Why?

```
/*@ requires \valid(p) && \valid(q);
    ensures \result >= *p && \result >= *q;
    ensures \result == *p || \result == *q;
*/
int max_ptr ( int *p, int *q ) {
    *p = 0;
    *q = 0;
    return 0 ;
}
```

- ▶ Our specification is incomplete
- ▶ Should say that the function cannot modify *p and *q

Assigns clause

The clause **assigns** v_1, v_2, \dots, v_N ;

- ▶ Part of the postcondition
- ▶ Specifies which (non local) variables can be modified by the function
- ▶ If nothing can be modified, specify **assigns \nothing**
- ▶ Avoids to state for all unchanged global variables v :
ensures \old(v) == v ;
- ▶ Avoids to forget one of them: explicit permission is required

Example 3 (Continued) - Solution

Run WP: `frama-c-gui -wp -wp-rte 03-max_ptr-4.c`

This completely specified program is proved:

```
/*@ requires \valid(p) && \valid(q);
    ensures \result >= *p && \result >= *q;
    ensures \result == *p || \result == *q;
    assigns \nothing;
*/
int max_ptr ( int *p, int *q ) {
    if ( *p >= *q )
        return *p ;
    return *q ;
}
```

The wrong version is not proved wrt. this specification.

Example 4

Specify and prove the following program (file 04-swap-0.c):

```
/* swaps two pointed values */  
void swap(int *a, int *b){  
    int tmp = *a ; *a = *b ; *b = tmp ;  
}
```

Example 4 - Solution

Run WP: `frama-c-gui -wp -wp-rte 04-swap-1.c`

This is the completely specified program:

```
/*@  
  requires \valid(a) && \valid(b);  
  requires \separated(a,b);  
  assigns *a, *b;  
  ensures *a == \old(*b) && *b == \old(*a);  
*/  
void swap(int *a, int *b){  
  int tmp = *a ; *a = *b ; *b = tmp ;  
}
```

Behaviors

Specification by cases

- ▶ Global precondition (**requires**) applies to all cases
- ▶ Global postcondition (**ensures**, **assigns**) applies to all cases
- ▶ Behaviors define contracts (refine global contract) in particular cases
- ▶ For each case (each **behavior**)
 - ▶ the subdomain is defined by **assumes** clause
 - ▶ the behavior's precondition is defined by **requires** clauses
 - ▶ it is supposed to be true whenever **assumes** condition is true
 - ▶ the behavior's postcondition is defined by **ensures**, **assigns** clauses
 - ▶ it must be ensured whenever **assumes** condition is true
- ▶ **complete behaviors** states that given behaviors cover all cases
- ▶ **disjoint behaviors** states that given behaviors do not overlap

Example 5

Specify using behaviors and prove the function `abs` (file `05-abs-0.c`):

```
// returns the absolute value of x  
int abs ( int x ) {  
    if ( x >= 0 )  
        return x ;  
    return -x ;  
}
```

Example 5 (Continued) - Solution

Run WP: `frama-c-gui -wp -wp-rte 05-abs-1.c`

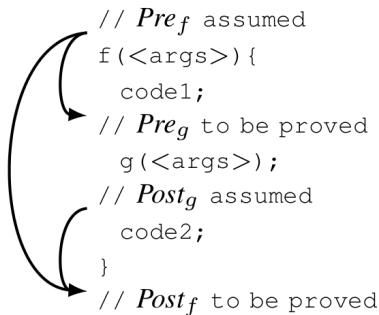
```

#include <limits.h>
/*@ requires x > INT_MIN;
    assigns \nothing;
    behavior pos:
        assumes x >= 0;
        ensures \result == x;
    behavior neg:
        assumes x < 0;
        ensures \result == -x;
    complete behaviors;
    disjoint behaviors;
*/
int abs ( int x ) {
    if ( x >=0 )
        return x ;
    return -x ;
}

```

Contracts and function calls

```
// Pref assumed
f(<args>){
  code1;
// Preg to be proved
  g(<args>);
// Postg assumed
  code2;
}
// Postf to be proved
```



Pre/post of the caller and of the callee have **dual roles** in the caller's proof

- ▶ Pre of the caller **is assumed**, Post of the caller **must be ensured**
- ▶ Pre of the callee **must be ensured**, Post of the callee **is assumed**

Example 6

Specify and prove the function `max_abs` (file `06-max_abs-0.c`):

```
int abs ( int x );  
int max ( int x, int y );  
  
// returns maximum of absolute values of x and y  
int max_abs( int x, int y ) {  
    x=abs(x);  
    y=abs(y);  
    return max(x,y);  
}
```

Example 6 (Continued) - Explain the proof failure

Run WP: `frama-c-gui -wp -wp-rte 06-max_abs-1.c`

```
#include<limits.h>
/*@ requires x > INT_MIN;
    ensures (x >= 0 ==> \result == x) && (x < 0 ==> \result == -x);
    assigns \nothing; */
int abs ( int x );

/*@ ensures \result >= x && \result >= y;
    ensures \result == x || \result == y;
    assigns \nothing; */
int max ( int x, int y );

/*@ ensures \result >= x && \result >= -x &&
    \result >= y && \result >= -y;
    ensures \result == x || \result == -x ||
    \result == y || \result == -y;
    assigns \nothing; */
int max_abs( int x, int y ) {
    x=abs(x);
    y=abs(y);
    return max(x,y);
}
```

Example 6 (Continued) - Explain the proof failure

Run WP: `frama-c-gui -wp -wp-rte 06-max_abs-2.c`

```
#include<limits.h>
/*@ requires x > INT_MIN;
    ensures (x >= 0 ==> \result == x) && (x < 0 ==> \result == -x);
    assigns \nothing; */
int abs ( int x );

/*@ ensures \result >= x && \result >= y;
    assigns \nothing; */
int max ( int x, int y );

/*@ requires x > INT_MIN;
    requires y > INT_MIN;
    ensures \result >= x && \result >= -x &&
        \result >= y && \result >= -y;
    ensures \result == x || \result == -x ||
        \result == y || \result == -y;
    assigns \nothing; */
int max_abs( int x, int y ) {
    x=abs(x);
    y=abs(y);
    return max(x,y);
}
```

Example 6 (Continued) - Solution

Run WP: `frama-c-gui -wp -wp-rte 06-max_abs-3.c`

```
#include<limits.h>
/*@ requires x > INT_MIN;
    ensures (x >= 0 ==> \result == x) && (x < 0 ==> \result == -x);
    assigns \nothing; */
int abs ( int x );

/*@ ensures \result >= x && \result >= y;
    ensures \result == x || \result == y;
    assigns \nothing; */
int max ( int x, int y );

/*@ requires x > INT_MIN;
    requires y > INT_MIN;
    ensures \result >= x && \result >= -x &&
        \result >= y && \result >= -y;
    ensures \result == x || \result == -x ||
        \result == y || \result == -y;
    assigns \nothing; */
int max_abs( int x, int y ) {
    x=abs(x);
    y=abs(y);
    return max(x,y);
}
```

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Loops and automatic proof

- ▶ What is the issue with loops? Unknown, **variable number of iterations**
- ▶ The only possible way to handle loops: **proof by induction**
- ▶ Induction needs a suitable **inductive property**, that is proved to be
 - ▶ satisfied just before the loop, and
 - ▶ satisfied after $k + 1$ iterations whenever it is satisfied after $k \geq 0$ iterations
- ▶ Such inductive property is called **loop invariant**
- ▶ The verification conditions for a loop invariant include two parts
 - ▶ **loop invariant initially holds**
 - ▶ **loop invariant is preserved** by any iteration

Loop invariants - some hints (*)

How to find a suitable loop invariant? Consider two aspects:

- ▶ identify **variables modified in the loop**
 - ▶ variable number of iterations prevents from deducing their values (relationships with other variables)
 - ▶ define their possible value intervals (relationships) after k iterations
 - ▶ use **loop assigns** clause to list variables that (might) have been assigned so far after k iterations
- ▶ identify realized actions, or **properties already ensured by the loop**
 - ▶ what **part of the job** already realized after k iterations?
 - ▶ what **part of the expected loop results** already ensured after k iterations?
 - ▶ why the next iteration can proceed as it does? ...

A **stronger property** on each iteration may be required to prove the final result of the loop

Some experience may be necessary to find appropriate loop invariants

Loop invariants - more hints (*)

Remember: a loop invariant must be true

- ▶ before (the first iteration of) the loop, even if no iteration is possible
- ▶ after any complete iteration even if no more iterations are possible
- ▶ in other words, any time before the loop condition check

In particular, a **for** loop

```
for(i=0; i<n; i++) { /* body */ }
```

should be seen as

```
i=0; // action before the first iteration
while( i<n )// an iteration starts by the condition check
{
  /* body */
  i++; // last action in an iteration
}
```


Loop termination

- ▶ Program termination is undecidable
- ▶ A tool cannot deduce neither the exact number of iterations, nor even an upper bound
- ▶ If an upper bound is given, a tool can check it by induction
- ▶ An upper bound on the number of remaining loop iterations is the key idea behind the loop variant

Terminology

- ▶ **Partial correctness:** if the function terminates, it respects its specification
- ▶ **Total correctness:** the function terminates, and it respects its specification

Loop variants - some hints (*)

- ▶ Unlike an invariant, a loop variant is an **integer expression**, not a predicate
- ▶ Loop variant is **not unique**: if V works, $V + 1$ works as well
- ▶ No need to find a precise bound, any working loop variant is OK
- ▶ To find a variant, **look at the loop condition**
 - ▶ For the loop **while**($\text{exp1} > \text{exp2}$), try **loop variant** $\text{exp1} - \text{exp2}$;
- ▶ In more complex cases: ask yourself why the loop terminates, and try to give an integer upper bound on the number of remaining loop iterations

Example 7

Specify and prove the function `reset_array` (file `07-reset_array-0.c`):

```
// writes 0 in each cell of the  
// array a of len integers  
void reset_array(int* a, int len){  
    for(int i = 0 ; i < len ; ++i){  
        a[i] = 0 ;  
    }  
}
```

Example 7 (Continued) - Solution

Run WP: `frama-c-gui -wp -wp-rte 07-reset_array-1.c`

```
/*@
  requires 0 <= len;
  requires \valid(a + (0 .. len-1));
  assigns a[0 .. len-1];
  ensures \forall integer i ; 0 <= i < len ==> a[i] == 0;
*/
void reset_array(int* a, int len){
  /*@
    loop invariant 0 <= i <= len ;
    loop invariant
      \forall integer j; 0 <= j < i ==> a[j] == 0 ;
    loop assigns i, a[0 .. len-1];
    loop variant len - i ;
  */
  for(int i = 0 ; i < len ; ++i){
    a[i] = 0 ;
  }
}
```

Example 8

Specify and prove the function `all_zeros` (file `08-all_zeros-0.c`):

```
// returns a non-zero value iff all elements  
// in a given array t of n integers are zeros  
int all_zeros(int t[], int n) {  
    int k;  
    for(k = 0; k < n; k++)  
        if (t[k] != 0)  
            return 0;  
    return 1;  
}
```

Example 8 (Continued) - Solution

Run WP: `frama-c-gui -wp -wp-rte 08-all_zeros-1.c`

```
/*@ requires n>=0 && \valid(t+(0..n-1));
   assigns \nothing;
   ensures \result != 0 <==>
     (\forall integer j; 0 <= j < n ==> t[j] == 0);
*/
int all_zeros(int t[], int n) {
  int k;
  /*@ loop invariant 0 <= k <= n;
     loop invariant \forall integer j; 0<=j<k ==> t[j]==0;
     loop assigns k;
     loop variant n-k;
  */
  for(k = 0; k < n; k++)
    if (t[k] != 0)
      return 0;
  return 1;
}
```

Example 9

Specify and prove the function `sqrt` (file `09-sqrt-0.c`):

```
/* takes as input an integer and returns  
   its (integer) square root */  
int root(int N){  
  int R = 0;  
  while((R+1)*(R+1)) <= N {  
    R = R + 1;  
  }  
  return R;  
}
```

Example 9 (Continued) - Solution

Run WP: `frama-c-gui -wp -wp-rte 09-sqrt-1.c`

```
/*@
  requires 0 <= N <= 1000000000;
  assigns \nothing;
  ensures \result * \result <= N ;
  ensures N < (\result+1) * (\result+1);
*/
int root(int N){
  int R = 0;
  /*@
    loop invariant 0 <= R * R <= N;
    loop assigns R;
    loop variant N-R;
  */
  while(((R+1)*(R+1)) <= N) {
    R = R + 1;
  }
  return R;
}
```


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Overview of the `memb` Module

- ▶ No dynamic allocation in Contiki
 - ▶ to avoid fragmentation of memory in long-lasting systems
- ▶ Memory is **pre-allocated** (in arrays of blocks) and attributed on demand
- ▶ The management of such blocks is realized by the `memb` module

The `memb` module API allows the user to

- ▶ initialize a `memb` store (i.e. pre-allocate an array of blocks),
- ▶ allocate or free a block,
- ▶ check if a pointer refers to a block inside the store
- ▶ count the number of allocated blocks

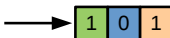
memb Data structure

```
struct memb {  
  unsigned short size;  
  unsigned short num;  
  char *count;  
  void *mem;  
};
```

For example:

size = 4

num = 3

count : 

1	0	1
---	---	---

mem : 

--	--	--	--	--	--	--	--	--	--	--	--

memb allocation function

```
void * memb_alloc(struct memb *m)
{
    for(int i = 0; i < m->num; ++i) {
        if(m->count[i] == 0) {
            ++(m->count[i]);
            int offset = i * m->size ;
            return (void *)((char *)m->mem + offset);
        }
    }
    return NULL;
}
```

Two behaviors:

- ▶ if a block is available, it is marked as busy, and its address is returned
- ▶ if no block is available, the function returns NULL

Example 10 – Prove `memb` allocation function

In the specification that is provided, there are missing parts (file `10-memb/memb.c`).

Hints:

- ▶ `requires`: the precondition of this function is some kind of validity
- ▶ `assumes`: we need to express that a free block exists
- ▶ `ensures`: `_memb_numfree` expresses the number of free blocks
- ▶ `loop invariant`: what do we know about previous blocks' status?

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Proof failures

A proof of a VC for some annotation can fail for **various reasons**:

- ▶ incorrect implementation (→ check your code)
- ▶ incorrect annotation (→ check your spec)
- ▶ missing or erroneous (previous) annotation (→ check your spec)
- ▶ insufficient timeout (→ try longer timeout)
- ▶ complex property that automatic provers cannot handle.

Analysis of proof failures

When a proof failure is due to the specification, the erroneous annotation may be **not obvious to find**. For example:

- ▶ proof of a “**loop invariant preserved**” may fail in case of
 - ▶ incorrect loop invariant
 - ▶ incorrect loop invariant in a previous, or inner, or outer loop
 - ▶ missing **assumes** or **loop assumes** clause
 - ▶ too weak precondition
 - ▶ ...
- ▶ proof of a **postcondition** may fail in case of
 - ▶ incorrect loop invariant (too weak, too strong, or inappropriate)
 - ▶ missing **assumes** or **loop assumes** clause
 - ▶ inappropriate postcondition in a called function
 - ▶ too weak precondition
 - ▶ ...

Analysis of proof failures (Continued)

- ▶ Additional statements (**assert**, **lemma**, ...) may help the prover
 - ▶ They can be provable by the same (or another) prover or checked elsewhere
- ▶ Separating independent properties (e.g. in separate, non disjoint behaviors) may help
 - ▶ The prover may get lost with a bigger set of hypotheses (some of which are irrelevant)

When nothing else helps to finish the proof:

- ▶ an **interactive proof assistant** can be used
- ▶ Coq, Isabelle, PVS, are not that scary: we may need only a small portion of the underlying theory

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Objectives of E-ACSL

- ▶ Frama-C initially designed as a static analysis platform
- ▶ Extended with plugins for **dynamic analysis**
- ▶ E-ACSL: runtime assertion checking tool
 - ▶ detect runtime errors
 - ▶ detect annotation failures
 - ▶ treat a concrete program run (i.e. concrete inputs)

E-ACSL plugin at a Glance

<http://frama-c.com/eacsl.html>

- ▶ convert E-ACSL annotations into C code
- ▶ implemented as a Frama-C plugin

```

int div(int x, int y) {
  /*@ assert y-1 != 0; */ E-ACSL
  return x / (y-1);
}

```

→

```

int div(int x, int y) {
  /*@ assert y-1 != 0; */
  e_acsl_assert(y-1 != 0);
  return x / (y-1);
}

```

- ▶ the general translation is more complex than it may look

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Example 1

Consider file 01-main1.c:

```
int f ( int a ) {
  int x, y;
  int sum, result;
  if(a == 0){
    x = 0; y = 0;
  }else{
    x = 5; y = 5;
  }
  sum = x + y;
  //@ assert sum != 0;
  result = 10 / sum;
  return result;
}
```

```
int main(void){
  f(42);
  f(0);
  return 0;
}
```

```
frama-c -e-acsl <main.c> -then-last \
  -print -ocode monitored_main.c
```

generates `monitored_main.c` that contains:

```
e_acsl_assert(sum != 0, "Assertion", "f", "sum != 0", 10);
```

Example 1

- ▶ Compiling `monitored_main.c` requires several libraries
- ▶ The E-ACSL plugin provides a convenient script to instrument and compile the program: `e-acsl-gcc.sh`

```
e-acsl-gcc.sh <main.c> -c -O monitored_main
```

- ▶ `monitored_main`: the executable without runtime monitoring
- ▶ `monitored_main.eacsl`: the executable **with** runtime monitoring

```
./monitored_main.eacsl
```

```
Assertion failed at line 10 in function f.
```

```
The failing predicate is:
```

```
sum != 0.
```

```
Aborted (core dumped)
```

Example 1, part 2

Consider file 01-main2.c:

```
int f ( int a ) {  
  int x, y;  
  int sum, result;  
  if(a == 0){  
    x = 0; y = 5;  
  }else{  
    x = 5; y = 0;  
  }  
  sum = x + y;  
  //@ assert sum != 0;  
  result = 10 / sum;  
  return result;  
}
```

```
int main(void){  
  f(42);  
  f(0);  
  return 0;  
}
```

./monitored_main.eacs1

- ▶ No output
- ▶ Both calls to f are error-free

Example 2

```

#include "stdlib.h"

struct list {
    struct list *next;
    int value;
};

/*@
    requires \valid(list);
    assigns *list;
*/
void list_init(struct list ** list) {
    *list = NULL;
}

int main(void){
    struct list ** l = malloc(sizeof(void *));
    list_init(l);
    free(l);
    list_init(l);
}

```

Example 2

Two features of the E-ACSL plugin:

- ▶ Function contract checking
- ▶ Runtime error detection

In the example (file 02–list1.c):

- ▶ At each call to `list_init` the contract is checked

```
./monitored_list.eacsl
```

```
Precondition failed at line 8 in function list_init.  
The failing predicate is:  
\valid(list).  
Aborted (core dumped)
```

Monitoring memory related constructs requires:

- ▶ keeping track of the program memory at runtime
- ▶ using a dedicated memory runtime library

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From ACSL to E-ACSL

- ▶ ACSL was designed for **static analysis tools** only
- ▶ based on logic and mathematics
- ▶ **cannot execute** any term/predicate (e.g. unbounded quantification)
- ▶ **cannot be used by dynamic analysis tools** (e.g. testing or monitoring)
- ▶ **E-ACSL**: **executable subset** of ACSL [Delahaye et al., RV'13]
 - ▶ few restrictions
 - ▶ one compatible semantics change

E-ACSL Restrictions

- ▶ **quantifications** must be guarded

```
\forall  $\tau_1$   $x_1, \dots, \tau_n$   $x_n$ ;
```

```
 $a_1$   $j = x_1$   $j = b_1$  && ... &&  $a_n$   $j = x_n$   $j = b_n$ 
```

```
==> p
```

```
\exists  $\tau_1$   $x_1, \dots, \tau_n$   $x_n$ ;
```

```
 $a_1$   $j = x_1$   $j = b_1$  && ... &&  $a_n$   $j = x_n$   $j = b_n$ 
```

```
&& p
```

- ▶ **sets** must be finite
- ▶ no lemmas nor axiomatics
- ▶ no way to express **termination** properties

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An Application to Contiki: Example 3

Example list_chop (started):

```
struct list
{
  struct list *next;
  int value;
};

/*@
  requires \valid(list);
  requires 0 <= length(*list);
*/
struct list * list_chop(struct list ** list){
  // removes the last element of the list
}
```

An Application to Contiki: Example 3

Example `list_chop` (cont'd):

```
int main(void){
  struct list node;
  node.value = 1;
  node.next = &node;

  struct list * l = &node;

  l = list_chop(&l);
}
```

- ▶ List `l` is cyclic, that can be detected by length
 - ▶ length should not be positive for a cyclic list
 - ▶ Our goal: verify the contract of `list_chop` and detect that `l` is cyclic
 - ▶ Contiki API: `int list_length(struct list **);`
- ⇒ the length of a list should be at most `INT_MAX`

An Application to Contiki: Example 3

```
/*@
  logic int length_aux{L}(struct list * l,
                          int n)=
    n < (int)0 ? ((int)-1) :
    l == NULL ? n :
    n < INT_MAX ?
      length_aux(l->next, (int)(1+n)) :
      ((int)-1);

  logic int length{L}(struct list * l) =
    length_aux(l, (int)0);
*/
```

- ▶ The E-ACSL specification language supports logical functions
 - ▶ The E-ACSL plugin does not yet
- ⇒ let us implement C function equivalent to length and use it to verify $0 \leq \text{length}(l)$ (that is, l is non cyclic) at runtime

An Application to Contiki: Example 3 – part 1 (WP)

Prove the equivalence of the logical and the recursive C functions, file 03-wp_list_1.c:

```

/*@ ensures \result == length_aux(l, n);
   @ assigns \nothing; */
int length_aux(struct list * l, int n){
  if (n < 0)
    return -1;
  else if (l == NULL)
    return n;
  else if (n < INT_MAX)
    return length_aux(l->next, n+1);
  else
    return -1;
}
/*@ ensures \result == length(l);
   @ assigns \nothing; */
int length(struct list * l){
  return length_aux(l, 0);
}

```

An Application to Contiki: Example 3 – part 2 (WP)

Prove the equivalence of the logical and the iterative C functions (additional annotations will be needed), file 03-wp_list_2.c:

```
/*@ ensures \result == length(list);
   @ assigns \nothing; */
int length(struct list * list){
  int len = 0;
  struct list * l = list;

  while(l != NULL && len < INT_MAX){
    l = l->next;
    len ++;
  }
  if(l!=NULL){
    return -1;
  }
  else
    return len;
}
```

An Application to Contiki: Example 3 – part 3 (E-ACSL)

Now with one of the C versions of length:

- ▶ We generate the annotated C code
- ▶ In function `__gen_e_acsl_list_chop` we add:

```
__e_acsl_assert(0<=length(*list),  
               (char*)"Precondition",  
               (char*)"list_chop",  
               (char*)"0<=length(l)",  
               60);
```

- ▶ option `-C` considers that the C file is already instrumented
- ▶ Exercise: compile the modified instrumented file `03-list_3.c`: and run it

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Possible Usage in Combination with Other Tools

- ▶ check unproved properties of **static analyzers** (e.g. Value, WP)
- ▶ check the absence of **runtime error** in combination with RTE
- ▶ check **memory consumption** and **violations** (use-after-free)
- ▶ help **testing tools** by checking properties which are not easy to observe
- ▶ complement program transformation tools
 - ▶ **temporal properties** (Aorai)
 - ▶ **information flow properties** (SecureFlow)

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We have presented how to:

- ▶ verify the absence of runtime errors with [Eva](#)
- ▶ formally specify functional properties with [ACSL](#)
- ▶ prove a programs respects its specification with [WP](#)
- ▶ verify annotations at runtime or detect runtime errors with [E-ACSL](#)

All of these and much more inside [Frama-C](#)

May be used for:

- ▶ [teaching](#)
- ▶ [academic](#) prototyping
- ▶ [industrial](#) applications

<http://frama-c.com>

Further reading

User manuals:

- ▶ user manuals for Frama-C and its different analyzers, on the website:
<http://frama-c.com>

About the use of WP:

- ▶ Introduction to C program proof using Frama-C and its WP plugin
Allan Blanchard
<https://allan-blanchard.fr/publis/frama-c-wp-tutorial-en.pdf>
- ▶ ACSL by Example
Jochen Burghardt, Jens Gerlach
<https://github.com/fraunhoferfokus/acsl-by-example>

Further reading

Tutorial papers:

- ▶ A. Blanchard, N. Kosmatov, and F. Loulergue. A Lesson on Verification of IoT Software with Frama-C (HPCS 2018)
- ▶ on deductive verification:
N. Kosmatov, V. Prevosto, and J. Signoles. A lesson on proof of programs with Frama-C (TAP 2013)
- ▶ on runtime verification:
 - ▶ N. Kosmatov and J. Signoles. A lesson on runtime assertion checking with Frama-C (RV 2013)
 - ▶ N. Kosmatov and J. Signoles. Runtime assertion checking and its combinations with static and dynamic analyses (TAP 2014)
- ▶ on test generation:
N. Kosmatov, N. Williams, B. Botella, M. Roger, and O. Chebaro. A lesson on structural testing with PathCrawler-online.com (TAP 2012)
- ▶ on analysis combinations:
N. Kosmatov and J. Signoles. Frama-C, A collaborative framework for C code verification: Tutorial synopsis (RV 2016)

Further reading

More details on the verification of Contiki:

- ▶ on the MEMB module:
F. Mangano, S. Duquennoy, and N. Kosmatov. A memory allocation module of Contiki formally verified with Frama-C. A case study (CRiSIS 2016)
- ▶ on the AES-CCM* module:
A. Peyrard, S. Duquennoy, N. Kosmatov, and S. Raza. Towards formal verification of Contiki: Analysis of the AES-CCM* modules with Frama-C (RED-IoT 2017)
- ▶ on the LIST module:
 - ▶ A. Blanchard, N. Kosmatov, and F. Loulergue. Ghosts for lists: A critical module of contiki verified in Frama-C (NFM 2018)
 - ▶ F. Loulergue, A. Blanchard, and N. Kosmatov. Ghosts for lists: from axiomatic to executable specifications (TAP 2018)