Secure Your Things:
Secure Development of IoT Software with Frama-C
Tutorial at IEEE SecDev 2018

Allan Blanchard, Nikolai Kosmatov, Frédéric Loulergue
some slides authored by Julien Signoles

Email: allan.blanchard@inria.fr, nikolai.kosmatov@cea.fr, frederic.loulergue@nau.edu

Cambridge, MA, September 30, 2018
Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP

Runtime Verification using E-ACSL

Conclusion
Internet of Things

- connect all devices and services
- 46 billions devices by 2021
- transport huge amounts of data

(c) Internet Security Buzz
And Security?

Mirai botnet, a DDoS nightmare turning Internet of Things into Botnet of things

Hacking a computer-aided sniper rifle

PACEMAKER HACKING FEAR RISES WITH CRITICAL RESEARCH REPORT

By Wagasa on October 22, 2018

By Andy Greenberg on 07/21/15

By Tom Spring on August 26, 2016, 2:55 pm

A. Blanchard, N. Kosmatov, F. Loulergue

Verification of IoT Software with Frama-C
Outline

Introduction

Security in the IoT
An overview of Frama-C
The Contiki operating system

Verification of absence of runtime errors using EVA

Deductive verification using WP

Runtime Verification using E-ACSL

Conclusion
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
  - *langua 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

```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;
}
```

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
Introduction

An overview of Frama-C

Plugin Gallery

- Abstract Interpretation
  - Eva
- Dynamic Analysis
  - PathCrawler
  - E-ACSL
- Specification Generation
  - RTE
  - Aoraï
- Formal Methods
  - Deductive Verification
    - Jessie
    - Wp
  - Code Transformation
    - Clang
    - Sparecode
    - Semantic constant folding
- Browsing of unfamiliar code
  - Metrics
  - Impact
  - Occurrence
  - Callgraph
  - Scope & Data-flow browsing
  - Ltest
  - StaDy
  - Sante

Some words in this talk

Presented in this talk
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
Outline

Introduction
  Security in the IoT
  An overview of Frama-C
  The Contiki operating system

Verification of absence of runtime errors using EVA

Deductive verification using WP

Runtime Verification using E-ACSL

Conclusion
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
...

A. Blanchard, N. Kosmatov, F. Loulergue
Verification of IoT Software with Frama-C
IEEE SecDev|2018 14 / 115
Outline

Introduction

Verification of absence of runtime errors using EVA
  Presentation of EVA
    Simple Examples
    An application to Contiki

Deductive verification using WP

Runtime Verification using E-ACSL

Conclusion
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
Outline

Introduction

Verification of absence of runtime errors using EVA
  Presentation of EVA
  Simple Examples
  An application to Contiki

Deductive verification using WP

Runtime Verification using E-ACSL

Conclusion
Example 1

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

```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; // 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`

```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; // 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`

```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; // 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`

```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;  // 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`

```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; // y can be non-initialized
    result = 10/sum;
    return result;
}
```

Alarm on initialization of y is reported, even with a bigger slevel
Example 4

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

```c
#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`

```c
#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`

```c
#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`

```c
#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`

```c
#include "stdlib.h"

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

Absence of runtime errors is proved
Outline

Introduction

Verification of absence of runtime errors using EVA
  Presentation of EVA
  Simple Examples
  An application to Contiki

Deductive verification using WP

Runtime Verification using E-ACSL

Conclusion
Overview of the aes-ccm Modules

- Critical! – Used for communication security
  - end-to-end confidentiality and integrity
  - 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 $\text{GF}(2^8)$
Examples 8, 9, 10

Analyze three versions of a part of the \texttt{aes} module

\textbf{Explore and explain the results}

Ex.8. Run Eva: \texttt{frama-c-gui aes1.c -val}

Ex.9. Run Eva: \texttt{frama-c-gui aes2.c -val}

Ex.10. Run Eva: \texttt{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`

Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP
  Overview of ACSL and WP
  Function contracts
  Programs with loops
  An application to Contiki
  My proof fails... What to do?

Runtime Verification using E-ACSL

Conclusion
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
Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP

Overview of ACSL and WP

Function contracts

Programs with loops

An application to Contiki

My proof fails... What to do?

Runtime Verification using E-ACSL

Conclusion
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

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: $\text{valid}(p)$, $\text{valid}(p+0..2)$, $\text{separated}(p+0..2,q+0..5)$, $\text{block\_length}(p)$
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...
- 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!
Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP
   Overview of ACSL and WP
   Function contracts
      Programs with loops
      An application to Contiki
      My proof fails... What to do?

Runtime Verification using E-ACSL

Conclusion
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:

```c
// 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:

```c
/*@ 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=INT_MIN`, `-x` cannot be represented by an `int` and overflows.
- Example: on 32-bit, `INT_MIN = -2^{31}` while `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.
Deductive verification using WP Function contracts

Example 1 (Continued) - Solution

Run WP: frama-c-gui -wp -wp-rte 01-abs-2.c
This completely specified program is proved:

```c
#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:

```c
// 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?

```c
/*@ 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 \result >= a && \result >= 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?

```c
/*@ 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?

```c
/*@ 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 \texttt{assigns v1, v2, \ldots, vN;}

- Part of the postcondition
- Specifies which (non local) variables can be modified by the function
- If nothing can be modified, specify \texttt{assigns \textbackslash nothing}
Example 2 (Continued) - Solution

Run WP: `frama-c-gui -wp -wp-rte 02-max-4.c`
This completely specified program is proved:

```c
/*@ 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:

```c
// 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:

```c
/*@ 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.
  - $\text{\textbackslash valid}(p)$ for one pointer $p$
  - $\text{\textbackslash valid}(p+0..2)$ 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?

```c
/*@ 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?

```c
/*@ 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** v1, v2, ... , vN;

- 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):

```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:

```c
/*@ 
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):

```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

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

// \textit{Pre}_f \textit{assumed}
\textbf{f}(\textit{<args>}){
    \textbf{code1;}
    // \textit{Pre}_g \textit{to be proved}
    \textbf{g}(\textit{<args>});
    // \textit{Post}_g \textit{assumed}
    \textbf{code2;}
}
// \textit{Post}_f \textit{to be proved}

Pre/post of the caller and of the callee have \textbf{dual roles} in the caller’s proof

- Pre of the caller \textbf{is assumed}, Post of the caller \textbf{must be ensured}
- Pre of the callee \textbf{must be ensured}, Post of the callee \textbf{is assumed}
Example 6

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

```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`

```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`

```c
#include <limits.h>
/*@ requires \(x > \text{INT\_MIN}\);
   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 \(x > \text{INT\_MIN}\);
 requires \(y > \text{INT\_MIN}\);
 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`

```c
#include <limits.h>
/*@
   requires \textbf{x} > \texttt{INT\_MIN};
   ensures \textbf{\texttt{x} >= 0} \implies \textbf{result} == \texttt{x} \&\& \textbf{\texttt{x} < 0} \implies \textbf{result} == -\texttt{x};
   assigns \texttt{nothing}; */
int abs ( int \textbf{x} );
*/

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

/*@ requires \textbf{x} > \texttt{INT\_MIN};
   requires \textbf{\texttt{y} > INT\_MIN};
   ensures \textbf{\texttt{result} >= x} \&\& \textbf{\texttt{result} >= -x} \&\& \textbf{\texttt{result} >= y} \&\& \textbf{\texttt{result} >= -y};
   ensures \textbf{\texttt{result} == x} \&\& \textbf{\texttt{result} == -x} \&\& \textbf{\texttt{result} == y} \&\& \textbf{\texttt{result} == -y};
   assigns \texttt{nothing}; */
int max_abs( int \textbf{x}, int \textbf{y} ) {
    \textbf{x}=abs(\textbf{x});
    \textbf{y}=abs(\textbf{y});
    \textbf{return} max(\textbf{x},\textbf{y});
}
```
Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP

Overview of ACSL and WP

Function contracts

Programs with loops

An application to Contiki

My proof fails... What to do?

Runtime Verification using E-ACSL

Conclusion
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

A. Blanchard, N. Kosmatov, F. Loulergue  Verification of IoT Software with Frama-C  IEEE SecDev|2018
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(exp1 > exp2 )`, try loop variant \( exp1 - exp2 \);
- 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):

```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`

```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`):

```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`

```c
/*@ requires n>0 && \valid(t+(0..n−1));
 assigns \nothing;
 ensures \result != 0 <=> (∀ integer j; 0 <= j < n ==> t[j] == 0);
*/

int all_zeros(int t[], int n) {
    int k;
    /*@ loop invariant 0 <= k <= n;*/
    /*@ loop invariant ∀ 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`):

```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`

```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;
}
```
Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP
  Overview of ACSL and WP
  Function contracts
  Programs with loops
  An application to Contiki
  My proof fails... What to do?

Runtime Verification using E-ACSL

Conclusion
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

```c
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

```c
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?
Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP
  Overview of ACSL and WP
  Function contracts
  Programs with loops
  An application to Contiki
  My proof fails... What to do?

Runtime Verification using E-ACSL

Conclusion
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
Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP

Runtime Verification using E-ACSL

Some Simple Examples

E-ACSL Specification Language

An Application to Contiki

Concluding Remarks

Conclusion
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);
}
```

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

Introduction
- Security in the IoT
- An overview of Frama-C
- The Contiki operating system

Verification of absence of runtime errors using EVA
- Presentation of EVA
- Simple Examples
- An application to Contiki

Deductive verification using WP
- Overview of ACSL and WP
- Function contracts
- Programs with loops
- An application to Contiki
- My proof fails... What to do?

Runtime Verification using E-ACSL
- Some Simple Examples
- E-ACSL Specification Language
- An Application to Contiki
- Concluding Remarks

Conclusion
Example 1

Consider file `main1.c`:

```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;
}
```

```c
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:

```c
    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:

```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;
}
```

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

./monitored_main.eacsl

- No output
- Both calls to f are error-free
Example 2

```c
#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
Outline

Introduction
  Security in the IoT
  An overview of Frama-C
  The Contiki operating system

Verification of absence of runtime errors using EVA
  Presentation of EVA
  Simple Examples
  An application to Contiki

Deductive verification using WP
  Overview of ACSL and WP
  Function contracts
  Programs with loops
  An application to Contiki
  My proof fails... What to do?

Runtime Verification using E-ACSL
  Some Simple Examples
  E-ACSL Specification Language
  An Application to Contiki
  Concluding Remarks

Conclusion
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

\[
\textbf{forall} \ \tau_1 \ x_1, \ldots, \tau_n \ x_n; \\
\quad a_1 \ j = x_1 \ j = b_1 \ \&\& \ldots \ \&\& \ a_n \ j = x_n \ j = b_n \\
\implies p
\]

\[
\textbf{exists} \ \tau_1 \ x_1, \ldots, \tau_n \ x_n; \\
\quad a_1 \ j = x_1 \ j = b_1 \ \&\& \ldots \ \&\& \ a_n \ j = x_n \ j = b_n \\
\quad \&\& \ p
\]

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

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP

Runtime Verification using E-ACSL

Some Simple Examples
E-ACSL Specification Language
An Application to Contiki
Concluding Remarks

Conclusion
例 3: list_chop 函数 (开始):

```c
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):

```c
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

```c
/*@  
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:

```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:

```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;
    }
}
```
Now with one of the C versions of length:

- We generate the annotated C code

- In function `__gen_e_acsl_list_chop` we add:

```c
__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
Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP

Runtime Verification using E-ACSL
  Some Simple Examples
  E-ACSL Specification Language
  An Application to Contiki
  Concluding Remarks

Conclusion
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 (Aoraï)
  - information flow properties (SecureFlow)
Outline

Introduction

Verification of absence of runtime errors using EVA

Deductive verification using WP

Runtime Verification using E-ACSL

Conclusion
Conclusion

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
Conclusion

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

▶ 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:
Conclusion

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:

- on the LIST module:
  - F. Loulergue, A. Blanchard, and N. Kosmatov. Ghosts for lists: from axiomatic to executable specifications (TAP 2018)