Secure Your Things:
Verification of IoT Software with Frama-C
Tutorial at HPCS 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

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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?
And Security?

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

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

Hackers remotely kill a Jeep on the highway—With me in it
And Security?

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

Hackers remotely kill a Jeep on the highway—with me in it

Pacemaker hacking fears rise with critical research report
And Security?

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

Hacking a computer-aided sniper rifle

PACEMAKER HACKING FEARS RISE WITH CRITICAL RESEARCH REPORT

by Tom Spring

August 26, 2016, 2:55 pm
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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)
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)

A. Blanchard, N. Kosmatov, F.Loulergue

Verification of IoT Software with Frama-C
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)
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 \implies
   (\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

- Abstract Interpretation
- Slicing
- Code Transformation
- Semantic constant folding
- Metrics
- Impact
- Occurrence
- Scope & Data-flow browsing

- Deductive Verification
- Formal Methods
- Browsing of unfamiliar code

- Specification Generation
- Dynamic Analysis
- E-ACSL
- PathCrawler
- StaDy
- Ltest
- Sante

- Plugin Gallery
- Eva
- Jessie
- Wp
- Aoraï
- RTE
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)
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    Simple Examples
    An application to Contiki

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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`

```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;
}
```
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;
}
```
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;
}
```
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;
}
```
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;
}
```
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);
}
```
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);
}
```
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;
}
```
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;
}
```
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;
}
```
Example 7

Run Eva: \texttt{frama-c-gui pointer3.c -val}

\begin{verbatim}
#include "stdlib.h"

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

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 \texttt{ccm} module

Explore and explain the results

Ex.11. Run Eva: \texttt{frama-c-gui ccm1.c -val}

Ex.12. Run Eva: \texttt{frama-c-gui ccm1.c -val -slevel 50}

Ex.13. Run Eva: \texttt{frama-c-gui ccm2.c -val -slevel 50}

Ex.14. Run Eva: \texttt{frama-c-gui ccm3.c -val -slevel 50}
Outline

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

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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
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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!
WP plugin

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  - Does it mean that the program is correct?
  - NO! If the specification is wrong, the program can be wrong!
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**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

```bash
★ 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.
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.
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?

```c
#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) - 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?

```c
#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 ;
}
```
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 \geq a && \result \geq 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 \texttt{v1}, \texttt{v2}, \ldots, \texttt{vN};}

- Part of the postcondition
- Specifies which (non local) variables can be modified by the function
- If nothing can be modified, specify \texttt{assigns \texttt{\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
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.
  - \texttt{\textbackslash valid}(p) for one pointer \( p \)
  - \texttt{\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`
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 \texttt{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 \texttt{assigns \nothing}
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:

```c
/*@ 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 $\text{abs}$ (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 \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

```c
// Pre_f assumed
f(<args>){
    code1;
    // Pre_g to be proved
    g(<args>);
    // Post_g assumed
    code2;
}
// Post_f 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):

```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 > 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`

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

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

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

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

should be seen as

```c
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):

```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;
}
```

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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;
}
```
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Overview of the \texttt{memb} Module

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

The \texttt{memb} module API allows the user to

- initialize a \texttt{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 : [image of memory allocation]
**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?
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Conclusion
A proof of a VC for some annotation can fail for various reasons:

- incorrect implementation  $(\rightarrow \text{check your code})$
- incorrect annotation  $(\rightarrow \text{check your spec})$
- missing or erroneous (previous) annotation  $(\rightarrow \text{check your spec})$
- insufficient timeout  $(\rightarrow \text{try longer timeout})$
- 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

```c
int div(int x, int y) {
   /*@ assert y-1 != 0; */
    return x / (y-1);
}
```
E-ACSL plugin at a Glance

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

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

- the general translation is more complex than it may look

```c
int div(int x, int y) {
    e_acsl_assert(y-1 != 0);
    return x / (y - 1);
}
```
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Example 1

Consider file 01–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;
}

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

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

```c
frama-c -e-acsl <main1.c> -then-last \
  -print -ocode monitored_main1.c
```
Example 1

Consider file 01–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;
}

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`
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
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:
\[
\text{sum} \neq 0.
\]
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; } 

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

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
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
Example 2

Two features of the E-ACSL plugin:

▶ Function contract checking
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In the example (file 02−list1.c):
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```
./monitored_list.eacsl

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

/premonitored_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**

\[
\forall \tau_1 x_1, \ldots, \tau_n x_n; \\
\ a_1 \neq x_1 \neq b_1 \ \&\& \ldots \ \&\& \ a_n \neq x_n \neq b_n \\
\implies p
\]

\[
\exists \tau_1 x_1, \ldots, \tau_n x_n; \\
\ a_1 \neq x_1 \neq b_1 \ \&\& \ldots \ \&\& \ a_n \neq x_n \neq b_n \\
\ \&\& \ p
\]

- **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):

```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
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);
*/
```
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
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 <= 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;
}
```
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:

```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
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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 (Aoraï)
  - information flow properties (SecureFlow)
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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
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)