# Frama-C
# A Collaborative Framework for C Code Verification

Tutorial at ISSRE 2017

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# Outline

# Frama-C Open Source Distribution

Framework for analyses of source code written in ISO 99 C
[Kirchner & al in FAC'15]

- developed by CEA LIST since 2005
- almost open source (LGPL 2.1)
- first open-source release aka Hydrogen in 2008
- last open-source release aka 15-Phosphorus in May 2017

http://frama-c.com

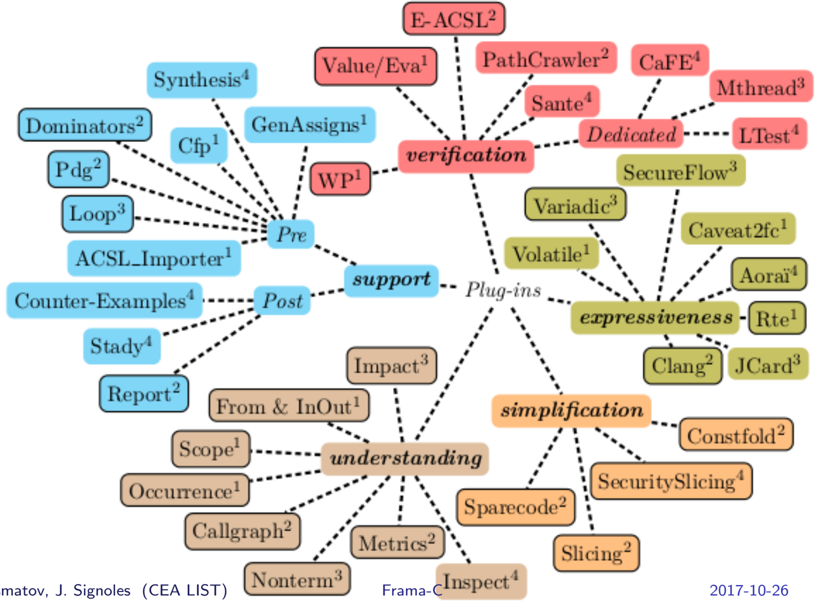
- analyze C code extended with ACSL annotations
- also proprietary extensions and distributions
- targets both academic and industrial usage

# Frama-C, a Collection of Tools

Several tools inside a single platform

- plug-in architecture *à la* Eclipse [S. @F-IDE'15]
- tools provided as plug-ins
  - 22 plug-ins in the open source distribution
  - outside open source plug-ins (*e.g.* Frama-Clang)
  - close source plug-ins, either at CEA (about 20) or outside
- plug-ins connected to a kernel
  - provides an uniform setting
  - provides general services
  - synthesizes useful information
  - analyzer combinations [Correnson & S. @FMICS'12]

# Frama-C Plug-ins Gallery



# Frama-C, a Development Platform

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

development of plug-ins by third party

- powerful low-cost analyser
- dedicated plug-in for specific task (coding rules verifier)
- dedicated plug-in for fine-grain parameterization
- extension of existing analysers

# Outline

Formal Specification and Deductive Verification with WP
- Overview of ACSL and WP
- Function contracts
- Programs with loops
- My proof fails... What to do?

Value Analysis

Structural Unit Testing with PathCrawler

Runtime Verification with E-ACSL

Combinations of Analyses

Conclusion

# Goal

In this part, we will see

- how to specify a C program using ACSL
- how to prove it with an automatic tool using Frama-C/WP
- how to understand and fix proof failures

# Objectives of Deductive Verification

Rigorous, mathematical proof of semantic properties of a program

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

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# ACSL: ANSI/ISO C Specification Language

## Presentation

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

## Basic Components

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

# WP plugin

- Hoare-logic based plugin, developed at CEA List
- Proof of semantic properties of the program
- Modular verification (function by function)
- Input: a program and its specification in ACSL
- WP generates verification conditions (VCs)
- Relies on Automatic Theorem Provers to discharge the VCs
  - Alt-Ergo, Simplify, Z3, Yices, CVC3, CVC4 ...
- WP manual at `http://frama-c.com/wp.html`
- If all VCs are proved, the program respects the given specification
  - Does it mean that the program is correct?

# WP plugin

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- WP manual at `http://frama-c.com/wp.html`
- If all VCs are proved, the program respects the given specification
  - Does it mean that the program is correct?
  - NO! If the specification is wrong, the program can be wrong!

# Outline



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# Contracts

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

Primary role of contracts

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

# Example 1

Specify and prove the following program:

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

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

- `frama-c-gui -wp file.c`

# Example 1 (Continued)

The basic proof succeeds for the following program:

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

- The returned value is not always as expected.

# Example 1 (Continued)

The basic proof succeeds for the following program:

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

- The returned value is not always as expected.
- For `x=INT_MIN`, `-x` cannot be represented by an `int` and overflows
- Example: on 32-bit, `INT_MIN`$= -2^{31}$ while `INT_MAX`$= 2^{31} - 1$

# 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

This is the completely specified program:

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

# Example 2

Specify and prove the following program:

```
// returns the maximum of x and y
int max ( int x, int y ) {
  if ( x >=y )
    return x ;
  return y ;
}
```

# Example 2 (Continued) - Find the error

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

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

# Example 2 (Continued) - a wrong version

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

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

# Example 2 (Continued) - a wrong version

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

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

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

# Example 2 (Continued) - Solution

This is the completely specified program:

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

# Example 3

Specify and prove the following program:

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

# Example 3 (Continued) - Explain the proof failure

Explain the proof failure with the option -wp-rte for the program:

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

# Example 3 (Continued) - Explain the proof failure

Explain the proof failure with the option -wp-rte for the program:

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

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

# Safety warnings: invalid memory accesses

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

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

# Example 3 (Continued) - Find the error

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

```
/*@ 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

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

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

# Example 3 (Continued) - a wrong version

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

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

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

# Assigns clause

The clause `assigns v1, v2, ... , vN;`

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

# Example 3 (Continued) - Solution

This is the completely specified program:

```
/*@ 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 ;
}
```

# 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 4

Specify using behaviors and prove the function abs:

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

# Example 4 (Continued) - Solution

```
#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

```
// 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 5

Specify and prove the function `max_abs`

```
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 5 (Continued) - Explain the proof failure for

```
#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 5 (Continued) - Explain the proof failure for

```
#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 5 (Continued) - Solution

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

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

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

# Outline



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# Loops and automatic proof

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

# Loop invariants - some hints

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

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

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

Some experience may be necessary to find appropriate loop invariants

# Loop invariants - more hints

Remember: a loop invariant must be true

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

In particular, a `for` loop

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

should be seen as

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

# Loop termination

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

## Terminology

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

# Loop variants - some hints

- Unlike an invariant, a loop variant is an integer expression, not a predicate
- Loop variant is not unique: if $V$ works, $V+1$ works as well
- No need to find a precise bound, any working loop variant is OK
- To find a variant, look at the loop condition
  - For the loop `while(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 6

Specify and prove the function `all_zeros`:

```
// 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 6 (Continued) - Solution

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

# Example 7

Specify and prove the function `find_min`:

```
// returns the index of the minimal element
// of the given array a of size length
int find_min(int* a, int length) {
  int min, min_idx;
  min_idx = 0;
  min = a[0];
  for (int i = 1; i<length; i++) {
    if (a[i] < min) {
      min_idx = i;
      min = a[i];
    }
  }
  return min_idx;
}
```

# Example 7 (Continued) - Solution

```
/*@ requires length > 0 && \valid(a+(0..length-1));
    assigns \nothing;
    ensures 0<=\result<length &&
      (\forall integer j; 0<=j<length ==> a[\result]<=a[j]);*/
int find_min(int* a, int length) {
  int min, min_idx;
  min_idx = 0;
  min = a[0];
  /*@ loop invariant 0<=i<=length && 0<=min_idx<length;
      loop invariant \forall integer j; 0<=j<i ==> min<=a[j];
      loop invariant a[min_idx]==min;
      loop assigns min, min_idx, i;
      loop variant length - i; */
  for (int i = 1; i<length; i++) {
    if (a[i] < min) {
      min_idx = i;
      min = a[i];
    }
  }
  return min_idx;
}
```

# Outline



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# Proof failures

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

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

# Analysis of proof failures

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

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

# Analysis of proof failures (Continued)

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

When nothing else helps to finish the proof:

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

# Outline

# Value Analysis

## Overview

Domain of variations of variables of the program

- abstract interpretation [Cousot & Cousot @POPL'77]
- automatic analysis
- correct over-approximation
- alarms for potential invalid operations
- alarms for potential invalid ACSL annotations
- ensures the absence of runtime error
- graphical interface: display the domain of each variable at each program point

# Value Historical Domains

- One hard-wired non-relation domain
  - 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
- ad-hoc trace partitioning
- alarms on potential RTE and invalid annotations
- highly optimized
  - excellent results on embedded code
  - possible usage in low-level C code

# Value Parameterization

- Value is automatic
- but requires fine-tuned parameterization to be precise/efficient
- trade-off between time efficiency *vs* memory efficiency *vs* precision
- stubbing: `main` function and missing library function
  - either provide C code or ACSL specification (usually, `assigns`)
  - similar to stubbing required by testing
- lots of parameters, but a few almost always useful

# Value Parameterization

## slevel

- slevel *n*: superpose up to *n* states during the analysis

```
// find the sum of all the multiples
// of 3 or 5 below 1000

int total = 0;
void add(int max, int x) { total += x; }

void sum(int max) {
  int i = 1;
  while (i <= max / 3) {
    add(max,3 * i);
    if (i % 3 !=0) add(max, 5*i);
    i++;
  }
}
int main() { sum(1000); return total; }
```

# Value Parameterization

## ACSL annotations

```
//find the sum of all the multiples of 3 or 5 below 1000

int total = 0;
/*@ requires x < max;
  @ requires x % 3 == 0 || x % 5 == 0; */
void add(int max, int x) { total += x; }

void sum(int max) {
  int i = 1;
  while (i <= max / 3) {
    add(max, 3 * i);
    if (i % 3 != 0) add(max, 5 * i);
    i++;
  }
}
int main() { sum(1000); return total; }
```

# Value Parameterization

## Solution of Euler project, problem 1

```
//find the sum of all the multiples of 3 or 5 below 1000

int total = 0;
/*@ requires x < max;
  @ requires x % 3 == 0 || x % 5 == 0; */
void add(int max, int x) { total += x; }

void sum(int max) {
  int i = 1;
  while (i <= max / 3) {
    add(max, 3 * i);
    if (i % 3 != 0 && 5 * i < max) add(max, 5 * i);
    i++;
  }
}
int main() { sum(1000); return total; }
```

# Value Parameterization

## case splitting

- case splitting through ACSL disjunctions

```
int gcd(int x, int y) {
  int a = x, b = y;
  while(b!=0) {
    int tmp = a % b;
    a = b; b = tmp;
  }
  return a;
}
```

# Value Parameterization

## case splitting

- case splitting through ACSL disjunctions

```
int gcd(int x, int y) {
  int a = x, b = y;
  /*@ assert b < 0 || b == 0 || b > 0; */
  while(b!=0) {
    int tmp = a % b;
    a = b; b = tmp;
    /*@ assert b < 0 || b == 0 || b > 0; */
  }
  return a;
}
```

# Plug-in Eva

## Main Features

- Frama-C plug-in for Value Analysis
- generic analysis on the abstract domain
- allow combination of abstract domains and some inter-reductions of their states
- easy to add new domain
  - Apron's domains
  - Venet's gauge
  - conditional predicate [Blazy, Bühler & Yakobowski @SCP'16]
  - continously added
  - contribute yourself :-)

# Plug-in Eva

## Design

the design relies on the separation between:

- values
  - abstraction of the possible C values of an expression
  - abstract transformers for arithmetic operators on expressions
  - communication interface for abstract domains
- domains
  - abstraction of the set of reachable states at a program point
  - abstract transformers of states through statements
  - can be queried for the values of some C expressions
- [Bühler, Yakobowski and Blazy @VMCAI'17]

# Eva Industrial Applications

## Scada System

can we guarantee absence of defaults in large system-level code?

- scada systems of 100+ kloc of C code
- highest certification requirements (IEC60880 class 1)
- pinpoint the undefined behaviors and help investigate their cause
- structural properties on memory separation and cyclic behaviors
- 80% code coverage, 200 alarms
- [Ourghanlian in NET'15]

# Derived analyses

- results from Eva are useful for other plug-ins
  - domains of variations
  - aliasing information
  - dependency information
- program dependency graph (PDG)
  - slicing
  - impact analysis
- domain specific analysis
  - information flow analysis [Assaf, S., Totel & Tronel @SEC'13]
  - concurrency analysis

# Outline

# Goal

In this part, we will see

- how to generate test cases using Frama-C/PathCrawler,
- how to specify test parameters,
- how to specify an oracle.

# Outline

1. Structural testing: a brief introduction
2. PathCrawler tool
3. Test parameters
4. Oracle and program debugging
5. Structural test for other properties/purposes
6. Strengths and limits of structural testing
7. Bypassing the limits

## Outline

1. **Structural testing: a brief introduction**
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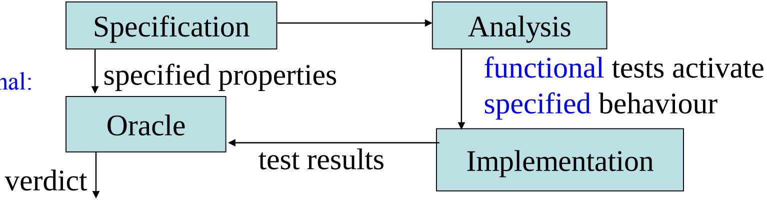
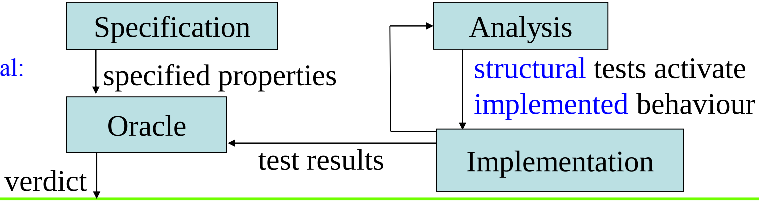
PathCrawler

# Structural vs. functional testing

Functional:




Structural:



# Unit structural testing is useful

Manually created functional test cases do not cover all the code

- Certain « functional » test cases can be missed
- Certain parts of code can depend on implementation choices and cannot be properly covered by the specification

Evaluation of structural coverage

Adding test cases to complete structural coverage

# Unit structural testing can be mandatory

**Development, evaluation and certification standards**

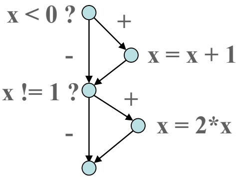
- **Common Criteria for IT Security Evaluation**
- **DO-178B (avionics)**
- **ECCS-E-ST-40C (space)**
- **IEC/EN 61508 (*Electronic Safety-related Systems*) & derived standards:**
  - ISO 26262 (automotive)
  - IEC/EN 50128 (rail)
  - IEC/EN 60601 (medical)
  - EC/EN 61513 (nuclear)
  - IEC/EN 60880 (nuclear safety-critical)
  - IEC/EN 61511 (process e.g. petrochemical, pharmaceutical)

# CFG and code coverage by example

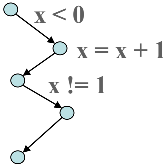
C code

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

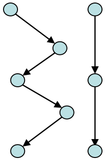
control-flow graph (CFG)



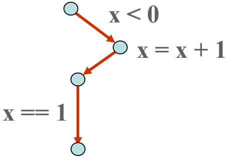

statement coverage



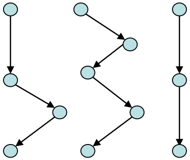

branch coverage



infeasible path




all-path coverage

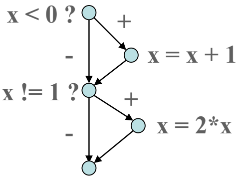


# Path predicate (path condition) by example

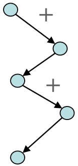
C code

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

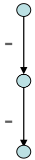
control-flow graph (CFG)



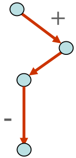

path predicate




$x_0 < 0 \wedge x_0 + 1 \neq 1$




$x_0 >= 0 \wedge x_0 = 1$




$x_0 < 0 \wedge x_0 + 1 = 1$

infeasible path

⇔

unsatisfiable path predicate

# Automated structural testing… Why?

Achieving desired test coverage manually is costly

Must be done again after any code modification

Infeasibility of a test objective can be difficult to show manually

Automated structural testing tools can be used

- to reach the uncovered objectives,
- to determine that some of them are unreachable,
- with a low cost overhead

## Outline

1. Structural testing: a brief introduction
2. **PathCrawler tool**
3. Test parameters
4. Oracle and program debugging
5. Strengths and limits of structural testing
6. Structural test for other properties/purposes
7. Bypassing the limits

# PathCrawler tool

- Concolic testing tool for C developed at CEA LIST
- Input: a complete compilable source code
- Automatically creates test cases to cover program paths (explored in depth-first search)
- Uses code instrumentation, concrete and symbolic execution, constraint solving
- Exact semantics: don't rely on concrete values to approximate the path predicate
- Similar to PEX, DART/CUTE, KLEE, SAGE etc.

PathCrawler

## PathCrawler explores the tree of feasible paths

*depth-first search with non-deterministic choice of suffix*

**test1: x = -5** $\quad x_0 < 0 \xrightarrow[x_1 = x_0 + 1]{+2} x_1 \neq 1 \xrightarrow[x_2 = 2x_1]{+4}$

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

## PathCrawler explores the tree of feasible paths

*depth-first search with non-deterministic choice of suffix*

**test1: x = -5** $x_0 < 0 \xrightarrow[x_1 = x_0 + 1]{+2} x_1 \neq 1 \xrightarrow[x_2 = 2x_1]{+4}$ $x_0 < 0 \wedge (x_0 + 1) \neq 1$

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PathCrawler

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$\xrightarrow{-4}$ $\quad x_0 < 0 \wedge (x_0 + 1) = 1$ ***infeas.***

```
int f(int x){
 if(x < 0)
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 return x; }
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PathCrawler

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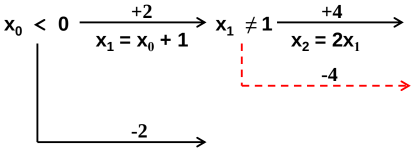


$x_0 < 0 \wedge (x_0 + 1) \neq 1$

$x_0 < 0 \wedge (x_0 + 1) = 1$ ***infeas.***

$x_0 \geq 0$

```
int f(int x){
 if(x < 0)
  x = x + 1;
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```

PathCrawler

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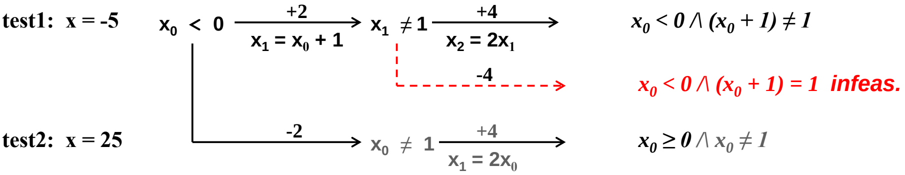


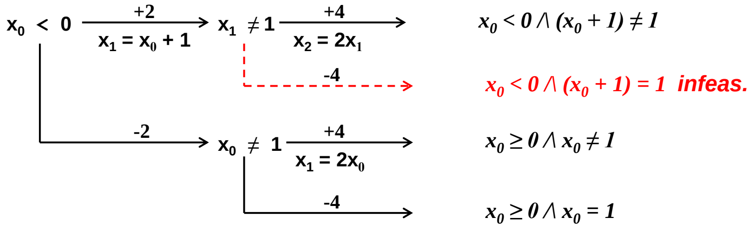

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

# PathCrawler explores the tree of feasible paths

*depth-first search with non-deterministic choice of suffix*

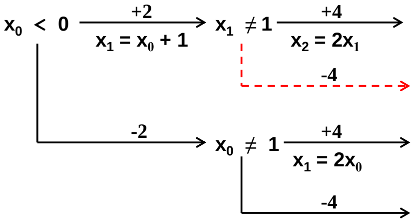
test1: x = -5

test2: x = 25



# PathCrawler explores the tree of feasible paths

*depth-first search with non-deterministic choice of suffix*




test1: x = -5 — $x_0 < 0 \wedge (x_0 + 1) \neq 1$

$x_0 < 0 \wedge (x_0 + 1) = 1$ **infeas.**

test2: x = 25 — $x_0 \geq 0 \wedge x_0 \neq 1$

test3: x = 1 — $x_0 \geq 0 \wedge x_0 = 1$

# pathcrawler-online.com

## Freely available test-case generation web service

- **Instead of open-source or demonstration version**
- **No porting, no installation, universal user interface**
- **Well adapted to**
  - Teaching
  - Use by project partners
  - Evaluation, understanding of Precondition and Oracle
- **Limited version (contact us for unlimited access)**

## During the tutorial

- **Browser: no cache recommended**
- **Do not start several test generation sessions in parallel**

## Example 1. Robust implementation of Tritype

Simple program `Tritype`

- inputs: three floating-point numbers `i`, `j`, `k`
- returns the type of the triangle with sides `i`, `j`, `k`:
  3 (not a triangle), 2 (equilateral), 1 (isosceles), 0 (other)

**Robust : validity of inputs is tested ("not a triangle")**

$\Rightarrow$ **Any test case can be interesting and useful**

**"Test with predefined params" on pathcrawler-online.com**

**Observe the number of test cases. Check the results.**

# PathCrawler outputs

- A suite of test cases including
  - Input values (check these for Example 1)
  - Concrete outputs (check these for Example 1)
  - Symbolic outputs (better illustrated by Example 5)
  - Path predicate (better illustrated by Example 5)
  - Test driver
  - Oracle verdict (better illustrated by Example 10)
- Explored program paths with
  - their status (covered, infeasible, assume violated …)
  - path predicate (only for covered paths in online version)

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## Example 2. Non robust implementation of Tritype

No validity check lines 10-13, no “not a triangle” answer

$\Rightarrow$ Are the test cases still interesting?

“Test with predefined params” on pathcrawler-online.com

Observe the number of test cases. Check the results.

Where is the problem?

Do we really want such input values in this case?

# Exercise 3. Customize test parameters for Tritype

**How to generate appropriate test cases only ?**

$\Rightarrow$ **define a precondition!**

**Exercise. Start from Example 2. "Customize test parameters"**

**- Restrict the domains of inputs `i`, `j`, `k` to non negative values:**

*[ 0 .. 1.7976931348623157e+308 ]*

**- Add 3 unquantified preconditions:**

$$i + j > k$$

$$j + k > i$$

$$i + k > j$$

**- Confirm parameters and check the results.**

PathCrawler

# Example 4. C Precondition for Tritype

**Another way to define a precondition**

**$\Rightarrow$ in a C function**

`Tritype_precond` returns 1 iff the precondition is verified

**"Customize test parameters" on pathcrawler-online.com to check that Pathcrawler has activated the C precondition.**

**Confirm & observe the number of test cases & results.**

## Test parameters

- **Define admissible inputs (precondition)**
  - Domains of input variables
  - Relations between variables…
- **Wrong test parameters may**
  - Indicate inexistent bugs (the bug is in the input)
  - Provoke runtime errors

# Example 5. Merge with default parameters

Merge of two sorted arrays `t1`, `t2` into a sorted array `t3`

- inputs: arrays `t1[3]`, `t2[3]`, `t3[6]` of fixed size

**"Test with predefined params" on pathcrawler-online.com**

**Check the concrete outputs.**

**What is wrong with the concrete outputs?**

**This example also illustrates well the information on array inputs, symbolic outputs and path predicate included in a test-case**

PathCrawler

# Exercise 6. Quantified precondition for Merge

**If the input arrays `t1` and `t2` are not ordered, `Merge` does not work!**

**Exercise. Start from Example 5. “Customize test parameters”**

- **Add two quantified preconditions (*INDEX* is a reserved word):**
  *for all INDEX*
  *such that INDEX < 2*
  *we have t1[ INDEX ]<= t1[ INDEX+1 ]*
  *for all INDEX*
  *such that INDEX < 2*
  *we have t2[ INDEX ]<= t2[ INDEX+1 ]*
- **Confirm parameters and check the results.**

**Are the input arrays `t1` and `t2` sorted now? Is `t3` sorted?**

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## Example 7. Merge with pointer inputs

**Merge of two sorted arrays `t1`, `t2` into a sorted array `t3`**

- **inputs: arrays `t1[ ]`, `t2[ ]`, `t3[ ]` of variable size, `l1` the size of `t1`, `l2` the size of `t2`, `l1+l2` the size of `t3`**
- **precondition** *t1, t2 ordered arrays* **predefined**
- **reduced domains of elements** [-100,100] **predefined**

**"Test with predefined params" on pathcrawler-online.com**

**Check the results.**

**Why are there errors?**

PathCrawler

# Exercise 8. Input arrays (pointers) size

`t1`, `t2`, `t3` **should contain resp.** `l1`, `l2`, `l1+l2` **allocated elements.**
**Wrong input array size => Runtime errors while executing tests!**

**Exercise. Start from Example 7. "Customize test parameters"**

- **Specify domains for dim(`t1`), dim(`t2`) , dim(`t3`)**

  *0 <= dim(t3) <= 6*
  *0 <= dim(t2) <= 3*
  *0 <= dim(t1) <= 3*

- **Add three unquantified preconditions:**

  *dim(t1) == l1*
  *dim(t2) == l1*
  *dim(t3) == l1 + l2*

- **Confirm parameters and check the results.**

**Are there errors? Why? How many test cases are generated?**

PathCrawler

## Partial test coverage : k-path criterion

- In presence of loops, all-path criterion may generate too many test cases
- The user may want to limit their number

- **k-path coverage restricts the all-path criterion to paths with at most k consecutive iterations of each loop (k=0,1,2…)**

PathCrawler

## Exercise 9. Merge with partial test coverage: k-path

**To reduce the number of test cases, modify test criterion.**

**Exercise. Continue Exercise 8 with the same test parameters you defined. “Customize test parameters”**

- **Set “Path selection strategy” to 2 (for k-path with k=2)**
- **Confirm parameters and check the results.**

**How many test cases are generated now?**

PathCrawler

# Outline

# Oracle

Role of an oracle:

- examines the inputs and outputs of each test
- decides whether the implementation has given the expected results
- provides a verdict (success, failure)

An oracle can be provided by

- another, or previous implementation
- checking the results without implementing the algorithm

## Exercise 10a. Oracle and debugging

Start from Example 10a, “Customize test parameters” to see an example of an oracle

**Is this oracle complete ?**

# Exercise 10b. Oracle and debugging

Start from Example 10b, “Customize test parameters” to see another example of an oracle

**Is this oracle complete ?**

## Exercise 10c. Oracle and debugging

Start from Example 10a, “Customize test parameters” to see the predefined oracle

**Exercise. Confirm parameters and check the results.**

**Can you find an error in the implementation?**

Hint: The paths of failed test cases have a common part…

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# Structural test for other properties or purposes

PathCrawler explores the implementation and can also be used to check:

- for **runtime errors** during program execution (seen in Ex.7)
- for **anomalies** detected during analysis of the covered paths:
  - uninitialised variables
  - buffer overflow
  - integer overflow
  - …
- whether the implementation performs **unnecessary computation**
- the effective **execution time** of each path (at least for one set of inputs), by running the generated tests on a platform which can measure execution time
- for unreachable or **“dead” code**: check infeasible partial paths.

  If all paths leading to the code are infeasible then the code is unreachable (for the given precondition): is this intentional ?

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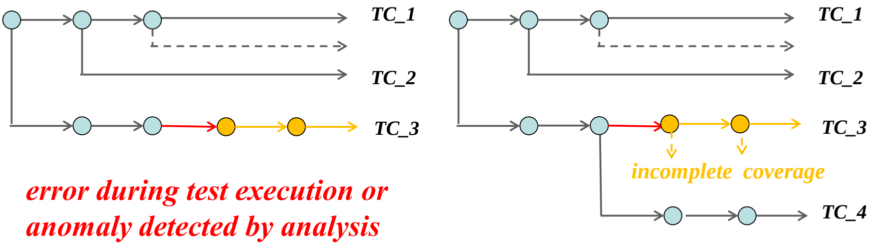
# Runtime error or anomaly: search space is pruned




PathCrawler

## Example Uninit. Uninitialised variable

In this example, the local variables are not always initialised before their value is read. This is a typical “anomaly”: probably a bug but does not cause a run-time error.

**“Test with predefined parameters” and check the results.**

**Are there any errors or warnings? Why?**
**Are all feasible paths covered?**

## Example UC. Unnecessary computation

`Bsearch` is an implementation of dichotomic search for value `x` in sorted array `A`.

**"Customize test parameters" to see the predefined oracle and parameters. Confirm them and check the results.**

**Examine the predicates and input values of the cases where x is present. Is this an efficient implementation?**

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PathCrawler

# Dichotomic search: structural vs. other strategies

**Example:** dichotomic search for a value int `x` in a sorted array int `A[10]`.

**Random testing:** Unlikely to construct cases in which x equals one of the elements of A and to detect false negatives (x not detected when present)

**Functional testing:** Constructs

- many cases in which x is present (probably from 1 to 10?) and
- fewer cases in which x is absent (1 or 2 ?)

**Structural testing:** Constructs a case

- for each position in A for which x can be detected and
- for each relation to elements of A for which absence of x is detected.

Structural test. constructs more presence cases than random, more absence cases than functional, rarely constructs cases where x is present by chance.

## Example Chance. Failures by chance?

`Bsearch` is another implementation of dichotomic search for value `x` in sorted array `A`. It contains a bug which can result in false positives (x present but not detected).

**The parameters are the same as in the previous example. Confirm them and check the results.**

**Is the presence or absence of x in A always determined by the path predicate?**

Hint: look at failing cases or those where x is present.

## Example 11. Limitations of structural testing

`Bsearch` is another erroneous implementation of dichotomic search for value `x` in sorted array `A`.

**The parameters are the same as in the previous example. Confirm them and check the results.**

**Are there any failures?**

# Limitations of structural testing

Structural testing is

- **effective** when a bug is **always revealed** by a path,
- **less so** when ***only some of the values*** which activate the path cause the bug to be revealed

**PathCrawler chooses arbitrary values to test each path**

**They may not be the values which will reveal a bug**

**We can make PathCrawler *go looking for bugs***

**by sub-dividing the paths**

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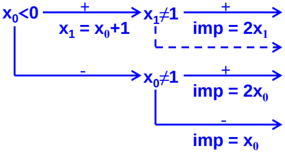
7. **Bypassing the limits**

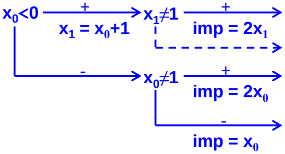
# Cross-checking conformity with a specification




## implementation

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

# Cross-checking conformity with a specification




implementation

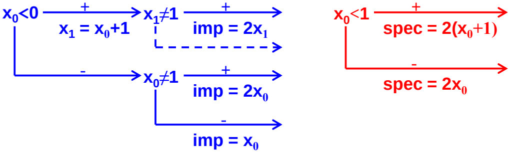
```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

specification

*If x is less than 1 then*
*the result should be 2(x + 1)*
*else the result should be 2x*

PathCrawler

# Cross-checking conformity with a specification




## implementation

```
int f(int x){
 if(x < 0)
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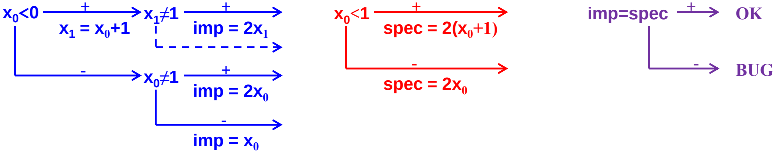
 if(x != 1)
  x = 2*x;
 return x; }
```

## specification

```
int spec_f(int x){
 if(x < 1)
  x = 2*(x + 1);
 else
  x = 2*x;
 return x; }
```

PathCrawler

# Cross-checking conformity with a specification




## implementation

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
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```

## specification

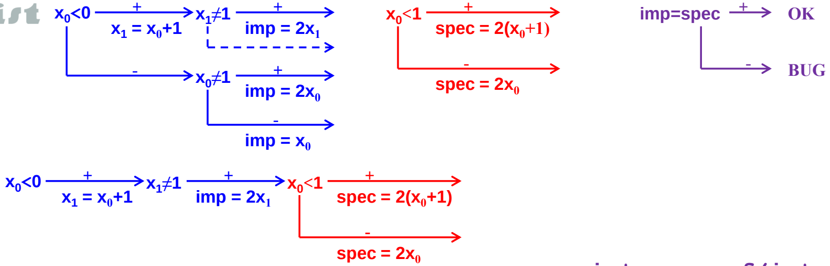
```
int spec_f(int x){
 if(x < 1)
  x = 2*(x + 1);
 else
  x = 2*x;
 return x; }
```

## comparison

```
int cross_f(int x){
 int imp = f(x);
 int spec=spec_f(x);
 if(imp!=spec)
   return 0;
 else return 1; }
```

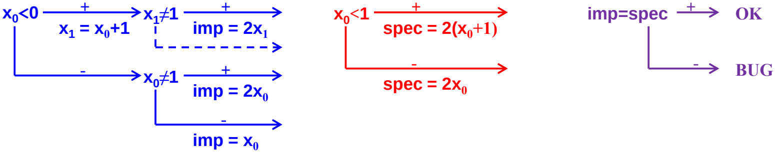
PathCrawler

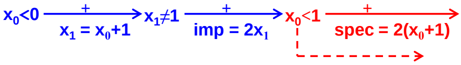
# Cross-checking conformity with a specification




```
int cross_f(int x){
 int imp = f(x);
 int spec=spec_f(x);
 if(imp!=spec)
   return 0;
 else return 1; }
```

# Cross-checking conformity with a specification




$$x_0 < 0 \wedge (x_0 + 1) \neq 1 \wedge x_0 < 1 \rightarrow x_0 < 0$$

$$x_0 < 0 \wedge (x_0 + 1) \neq 1 \wedge x_0 \geq 1$$

```
int cross_f(int x){
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PathCrawler

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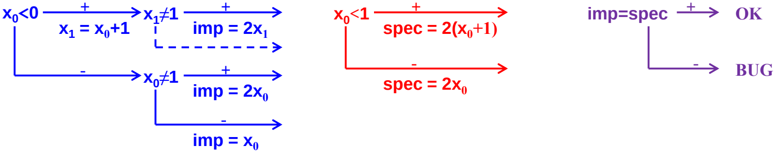


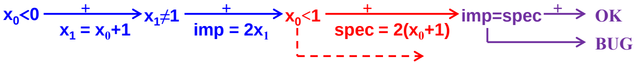


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PathCrawler

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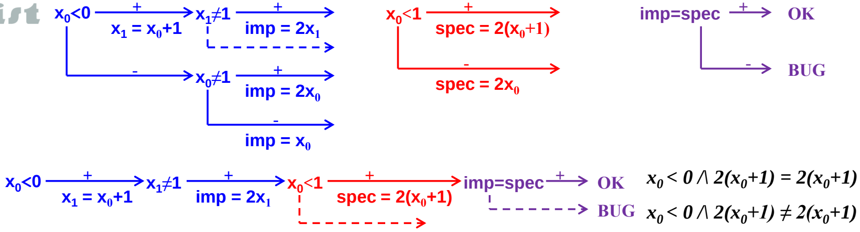

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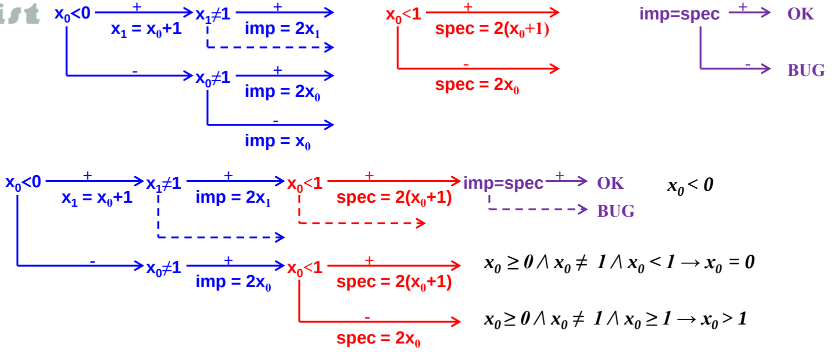


PathCrawler

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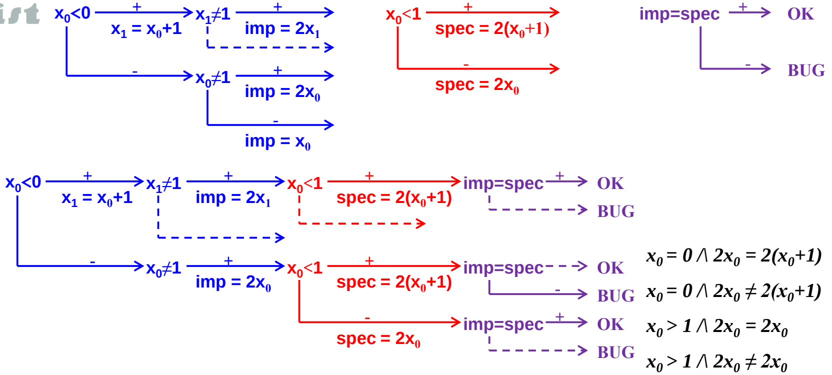
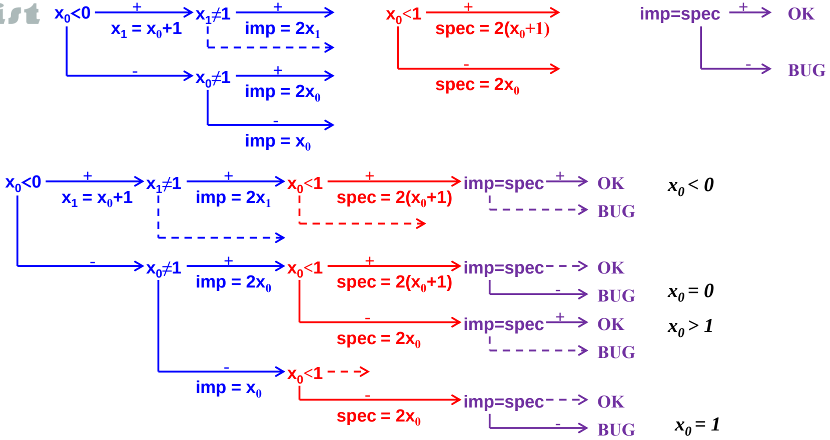



PathCrawler

# Cross-checking conformity with a specification



## Example 12. Testing conformity with a specification

`Spec_Bsearch` is a specification for `Bsearch`, similar to the oracle. Test function `CompareBsearchSpec` that

- stores inputs, calls `Bsearch`,
- calls `Spec_Bsearch` to provide a verdict.

All-path testing will try cover all combinations of paths in `Bsearch` and `Spec_Bsearch`.

**"Customize test parameters" to see the predefined oracle and parameters. Confirm them and check the results.**

**Why are failures reported this time? Can you find the bug?**

# Outline

# Goal

In this part, we will see

- the differences between ACSL and E-ACSL
- how to check E-ACSL properties at runtime
- how static analyses improve efficiency of the monitor

# 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, K. & S. @RV'13]
  - few restrictions
  - one compatible semantics change

# E-ACSL Restrictions

- quantifications must be guarded

$$\texttt{\textbackslash forall}\ \tau_1\ x_1, \ldots, \tau_n\ x_n;\ a_1 \texttt{ <= } x_1 \texttt{ <= } b_1 \texttt{ \&\& } \ldots \texttt{ \&\& } a_n \texttt{ <= } x_n \texttt{ <= } b_n \texttt{ ==> } p$$

$$\texttt{\textbackslash exists}\ \tau_1\ x_1, \ldots, \tau_n\ x_n;\ a_1 \texttt{ <= } x_1 \texttt{ <= } b_1 \texttt{ \&\& } \ldots \texttt{ \&\& } a_n \texttt{ <= } x_n \texttt{ <= } b_n \texttt{ \&\& } p$$

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

# E-ACSL Integers

- mathematical integers to preserve ACSL semantics
- many advantages compared to bounded integers
  - automatic theorem provers work much better with such integers than with bounded integers arithmetics
  - specify without implementation details in mind
  - still possible to use bounded integers when required
  - much easier to specify overflows

# Error in annotations?

- ACSL logic is total and 1/0 is logically significant
  - help the user to write simple specification like u/v == 2
  - 1/0 is defined but not executable
- E-ACSL logic is 3-valued
  - the semantics of 1/0 is "undefined"
  - lazy operators `&&`, `||`, `_?_:_`, `==>`
  - Chalin's Runtime Assertion Checking semantics
  - consistent with ACSL: valid (resp. invalid) E-ACSL predicates remain valid (resp. invalid) in ACSL
  - evaluating an undefined term must not crash

# E-ACSL plug-in at a Glance

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

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

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

E-ACSL ⟶

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

# E-ACSL plug-in at a Glance

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```
int div(int x, int y) {
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```

$\xrightarrow{\text{E-ACSL}}$

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

- the general translation is more complex than it may look

# E-ACSL Integer Support

- use GMP library for mathematical integers

```
/*@ assert y-1 == 0; */
mpz_t e_acsl_1, e_acsl_2, e_acsl_3, e_acsl_4;
int e_acsl_5;
mpz_init_set_si(e_acsl_1, y);                  // e_acsl_1 = y
mpz_init_set_si(e_acsl_2, 1);                  // e_acsl_2 = 1
mpz_init(e_acsl_3);
mpz_sub(e_acsl_3, e_acsl_1, e_acsl_2);         // e_acsl_3 = y-1
mpz_init_set_si(e_acsl_4, 0);                  // e_acsl_4 = 0
e_acsl_5 = mpz_cmp(e_acsl_3, e_acsl_4);        // (y-1) == 0
e_acsl_assert(e_acsl_5 == 0);                  // runtime check
mpz_clear(e_acsl_1); mpz_clear(e_acsl_2);      // deallocate
mpz_clear(e_acsl_3); mpz_clear(e_acsl_4);
```

# E-ACSL Integer Support

- use GMP library for mathematical integers

```
/*@ assert y-1 == 0; */
mpz_t e_acsl_1, e_acsl_2, e_acsl_3, e_acsl_4;
int e_acsl_5;
mpz_init_set_si(e_acsl_1, y);                // e_acsl_1 = y
mpz_init_set_si(e_acsl_2, 1);                // e_acsl_2 = 1
mpz_init(e_acsl_3);
mpz_sub(e_acsl_3, e_acsl_1, e_acsl_2);       // e_acsl_3 = y-1
mpz_init_set_si(e_acsl_4, 0);                // e_acsl_4 = 0
e_acsl_5 = mpz_cmp(e_acsl_3, e_acsl_4);      // (y-1) == 0
e_acsl_assert(e_acsl_5 == 0);                // runtime check
mpz_clear(e_acsl_1); mpz_clear(e_acsl_2);    // deallocate
mpz_clear(e_acsl_3); mpz_clear(e_acsl_4);
```

- how to restrict GMPs as most as possible? on-the-fly typing

almost no GMP in practice

[Jakobsson, K. & S. @JFLA'15]

# E-ACSL Memory Observation

- memory-related constructs like `\valid`, `\initialized`, `\block_length`, `\base_addr`, `\offset` require to know the memory structure at runtime
- C library for memory observation
  - Shadow memory efficient implementation
  - [Vorobyov, S. & K. @ISMM'17]
  - express more properties than related work for comparable overheads
- once again the translation is quite heavy
- dataflow analysis to instrument the code only when required
  - backward
  - over-approximating
  - parameterized by an alias analysis
  - [Jakobsson, K. & S. in J. of SCP'16]

# E-ACSL Memory Observation

```
void f(void) {
  int x, y, z, *p;

  p = &x;
  x = 0;
  y = 1;
  z = 2;

  /*@ assert \valid(p); */

  *p = 3;

}
```

# E-ACSL Memory Observation

```
void f(void) {
  int x, y, z, *p;
  // allocations of local variables
  __store_block((void *)(&p), 4U); __store_block((void *)(&z), 4U);
  __store_block((void *)(&y), 4U); __store_block((void *)(&x), 4U);
  __full_init((void *)(&p)); p = &x; // initialization of p
  __full_init((void *)(&x)); x = 0;  // initialization of x
  __full_init((void *)(&y)); y = 1;  // initialization of y
  __full_init((void *)(&z)); z = 2;  // initialization of z
  // validity check
  /*@ assert \valid(p); */
  { int __e_acsl_initialized, __e_acsl_and;
    __e_acsl_initialized = __initialized((void *)(&p),sizeof(int *));
    if (__e_acsl_initialized) { int __e_acsl_valid;
      __e_acsl_valid = __valid((void *)p, sizeof(int));
      __e_acsl_and = __e_acsl_valid;
    } else __e_acsl_and = 0;
    e_acsl_assert(__e_acsl_and); }
  *p = 3;
  // free allocated variables
  __delete_block((void *)(&p)); __delete_block((void *)(&z));
  __delete_block((void *)(&y)); __delete_block((void *)(&x));
}
```

# E-ACSL Memory Observation

```
void f(void) {
  int x, y, z, *p;
  // allocations of local variables
  __store_block((void *)(&p), 4U); __store_block((void *)(&z), 4U);
  __store_block((void *)(&y), 4U); __store_block((void *)(&x), 4U);
  __full_init((void *)(&p)); p = &x; // initialization of p
  __full_init((void *)(&x)); x = 0;  // initialization of x
  __full_init((void *)(&y)); y = 1;  // initialization of y
  __full_init((void *)(&z)); z = 2;  // initialization of z
  // validity check
  /*@ assert \valid(p); */
  { int __e_acsl_initialized, __e_acsl_and;
    __e_acsl_initialized = __initialized((void *)(&p),sizeof(int *));
    if (__e_acsl_initialized) { int __e_acsl_valid;
      __e_acsl_valid = __valid((void *)p, sizeof(int));
      __e_acsl_and = __e_acsl_valid;
    } else __e_acsl_and = 0;
    e_acsl_assert(__e_acsl_and); }
  *p = 3;
  // free allocated variables
  __delete_block((void *)(&p)); __delete_block((void *)(&z));
  __delete_block((void *)(&y)); __delete_block((void *)(&x));
}
```

# Possible Usage in Combination with Other Tools

- check the absence of runtime error in combination with RTE
- check unproved properties of static analyzers (e.g. Value, WP)
  - [Pariente & S. @SSTIC'17]
- help testing tools by checking properties which are not easy to observe
- complement program transformation tools
  - temporal properties (Aoraï)
  - information flow properties (SecureFlow)
    - [Barany & S. @TAP'17]

# Outline

Formal Specification and Deductive Verification with WP

Value Analysis

Structural Unit Testing with PathCrawler

Runtime Verification with E-ACSL

Combinations of Analyses

- Detecting runtime errors by static analysis and testing (SANTE)
- Deductive verification assisted by testing (STADY)
- Optimizing testing by value analysis and weakest precondition (LTest)

Conclusion

# Goal

In this part, we

- describe some combinations of static and dynamic analyses,
- illustrate their implementation as plugins of Frama-C.

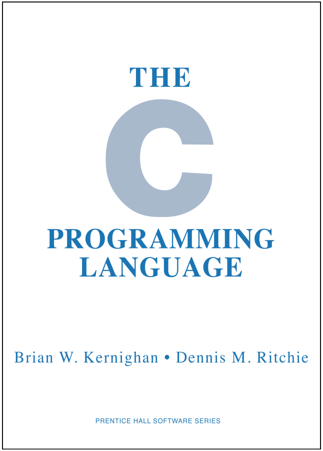
# Outline

# The C language is risky!

- Low-level operations
- Widely used for critical software
- Lack of security mechanisms

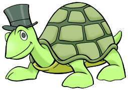
Runtime errors are common:

- Division by 0
- Invalid array index
- Invalid pointer
- Non initialized variable
- Out-of-bounds shifting
- Arithmetical overflow
- ...



# SANTE: Goals

Detection of runtime errors: two approaches



Static analysis

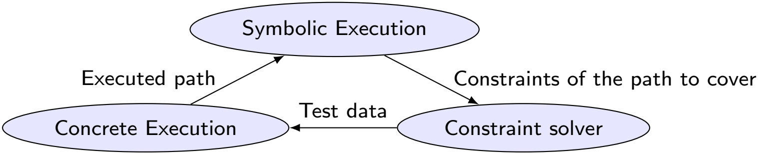
Issue: leaves unconfirmed errors that can be safe

Testing

Issue: cannot detect all errors if test coverage is partial

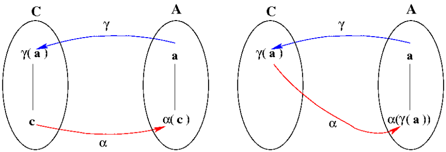
Goal: Combine both techniques to detect runtime errors more efficiently

# Plugin PathCrawler for test generation



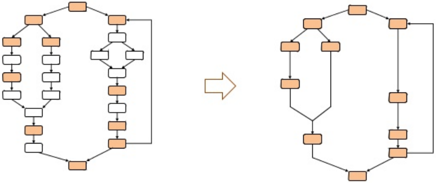

- Performs Dynamic Symbolic Execution (DSE)
- Automatically creates test data to cover program paths (explored in depth-first search, [Botella et al. AST 2009])
- Uses code instrumentation, concrete and symbolic execution, constraint solving
- Exact semantics: doesn't approximate path constraints
- Similar to PEX, DART/CUTE, KLEE, SAGE, etc.
- Online version: `pathcrawler-online.com`

# Plugin "VALUE" for value analysis



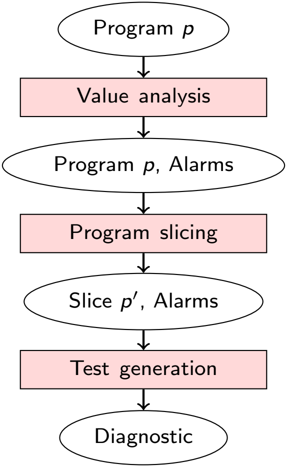

- Based on abstract interpretation [Cousot, POPL 1977]
- Computes an overapproximation of sets of possible values of variables at each instruction
- Considers all possible executions
- Reports alarms when cannot prove absence of errors

# Plugin Slicing



- Simplifies the program using control and data dependencies
- Preserves the executions reaching a point of interest (*slicing criterion*) with the same behavior
- Example of slicing criteria: instructions, annotations (alarms), function calls and returns, read and write accesses to selected variables. . .

# SANTE: Methodology for detection of runtime errors




- Value analysis detects alarms
- Slicing reduces the program (w.r.t. one or several alarms)
- Testing (PathCrawler) is used to generate tests on a reduced program to diagnose alarms (after adding error branches to trigger errors)
- Diagnostic
  - bug if a counter-example is generated
  - if not, and all paths were explored, the alarm is safe
  - otherwise, unknown

# SANTE: Experiments

- 9 benchmarks with known errors (from Apache, libgd, . . . )

Alarm classification:

- all known errors found by SANTE
- SANTE leaves less unclassified alarms than VALUE (by 88%) or PathCrawler (by 91%) alone

Program reduction:

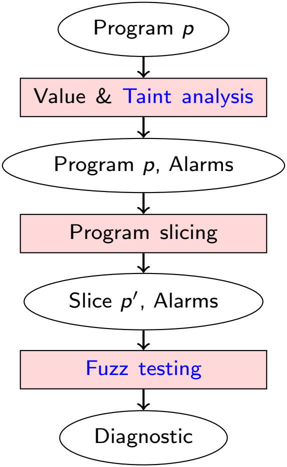
- 32% in average, up to 89% for some examples
- program paths in counter-examples are in average 19% shorter

Execution time:

- Average speedup w.r.t. testing alone is 43% (up to 98% for some examples)

[Chebaro et al. TAP 2009, TAP 2010, SAC 2012, ASEJ 2014]

# Application to security




- Reused in EU FP7 project STANCE (CEA LIST, Dassault, Search Lab, FOKUS,...)
- Taint analysis to identify most security-relevant alarms
- Fuzz testing (Flinder tool) for efficient detection of vulnerabilities
- Applied to the recent Heartbleed security flaw (2014) in OpenSSL, other case studies in progress
- [Kiss et al., HVC 2015]

# Outline

# Plugin WP for deductive verification

$$\dfrac{\dfrac{\{\,A\wedge b\,\}\;c\;\{\,B\,\} \qquad \dfrac{(A\wedge\neg b)\Rightarrow B}{\{\,(A\wedge\neg b)\,\}\ \mathtt{skip}\ \{\,B\,\}}}{\{\,A\,\}\ \mathtt{if}\ b\ \mathtt{then}\ c\ \mathtt{else}\ \mathtt{skip}\ \{\,B\,\}}}{\{\,A\,\}\ \mathtt{if}\ b\ \mathtt{then}\ c\ \{\,B\,\}}$$

- Based on Weakest Precondition calculus [Dijkstra, 1976]
- Proves that a given program respects its specification

The enemy: proof failures, i.e. unproven properties

- can result from very different reasons
  - an error in the code,
  - an insufficient precondition,
  - a too weak subcontract (e.g. loop invariant, callee's contract),
  - a too strong postcondition,...
- often require costly manual analysis

# Example: a C program annotated in ACSL

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

Can be proven in Frama-C/WP

# Example: An erroneous version

```
/*@ 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 assigns k;
      loop variant n-k;
  */
  for(k = 0; k < n; k++)
    if (t[k] != 0)
      return 0;
  return 1;
}
```

Postcondition unproven...

...because of a missing loop invariant.

The reason could also be a wrong precond, or postcond., or code

# STADY: Goals

- Help the validation engineer to understand and fix the proof failures
- Provide a counter-example to illustrate the issue
- Do it automatically and efficiently

# STADY: Methodology for diagnosis of proof failures

- Define three kinds of proof failures:
  - non-compliance (between the code and its specification)
  - subcontract weakness (for a loop or a called function)
  - prover incapacity
- Perform dedicated instrumentation allowing to detect non-compliances and subcontract weaknesses
- Apply testing (PathCrawler) to try to find a counter-example and to classify the proof failure
- Indicate a more precise feedback (if possible, with a counter-example) to help the user to understand and to fix the proof failure

# STADY: Initial experiments

- 20 annotated (provable) programs (from [Burghardt, Gerlach])
- 928 mutants generated (erroneous code, erroneous or missing annotation)
- STADY is applied to classify proof failures

Alarm classification:

- STADY classified 97% proof failures

Execution time: comparable to WP

- WP takes in average 2.6 sec. per mutant (13 sec. per unproven mutant)
- STADY takes in average 2.7 sec. per unproven mutant

Partial coverage:

- Testing with partial coverage remains efficient in STADY

[Petiot et al. TAP 2014, SCAM 2014, TAP 2016]

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Conclusion

# Context: white-box testing

- Generate a test input
- Run it and check for errors
- Estimate coverage: if enough, then stop, else loop

Coverage criteria (decision, mcdc, mutants, etc.) play a major role

- generate tests, decide when to stop, assess quality of testing

The enemy: Uncoverable test objectives

- waste generation effort, imprecise coverage ratios
- cause: structural coverage criteria are ... structural
- detecting uncoverable test objectives is undecidable

Recognized as a hard and important issue in testing

- no practical solution, not so much work (compared to test gen.)
- **real pain** (e.g. aeronautics, mutation testing)

# LTest: Goals

We focus on white-box (structural) coverage criteria

Automatic detection of uncoverable test objectives

- a *sound* method
- applicable to a large class of coverage criteria
- strong detection power, reasonable speed
- rely as much as possible on existing verification methods

Note. The test objective "reach location *loc* and satisfy predicate *p*" is uncoverable $\Leftrightarrow$ the assertion `assert (`$\neg p$`);` at location *loc* is valid

# Example: program with two uncoverable test objectives

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
  int res;
  if(x+a >= x)
    res = 1;    // the only possible outcome
  else
    res = 0;
 // l1: res == 0
 // l2: res == 2
}
```

# Example: program with two valid assertions

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0
 //@ assert res != 2
}
```

# Example: program with two valid assertions

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0     // both VALUE and WP fail
 //@ assert res != 2     // detected as valid
}
```

# LTest Methodology: Combine VALUE $\oplus$ WP

Goal: get the best of the two worlds

- Idea: VALUE passes to WP the global information that WP needs

Which information, and how to transfer it?

- VALUE computes variable domains
- WP naturally takes into account assumptions (`assume`)

Proposed solution:

- **VALUE exports computed variable domains in the form of WP-assumptions**

# Example: alone, both VALUE and WP fail

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {



  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0     // both VALUE and WP fail

}
```

# Example: VALUE⊕WP

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
 //@ assume 0 <= a <= 20
 //@ assume 0 <= x <= 1000 // VALUE inserts domains...
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0


}
```

# Example: VALUE⊕WP

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
 //@ assume 0 <= a <= 20
 //@ assume 0 <= x <= 1000 // VALUE inserts domains...
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0        // ...  and WP succeeds!

}
```

# LTest: Results and Experiments

- automatic, sound and generic method
- new combination of existing verification techniques
- experiments for 12 programs and 3 criteria (CC, MCC, WM):
  - strong detection power (95%),
  - reasonable detection speed ($\leq$ 1s/obj.),
  - test generation speedup (3.8x in average),
  - more accurate coverage ratios (99.2% instead of 91.1% in average, 91.6% instead of 61.5% minimum)

[Bardin et al. ICST 2014, TAP 2014, ICST 2015]

# Outline

# Conclusion

We have presented how to:

- formally specify C code with ACSL
- prove programs with WP
- verify the absence of runtime errors with Value
- generate test cases with PathCrawler
- verify annotations at runtime with E-ACSL
- combine analyses in different ways

All of these and much more inside Frama-C

May be used for:

- teaching
- academic prototyping
- industrial applications

http://frama-c.com

# Some Industrial Applications

- Airbus & Atos: WP and home-made plug-ins for avionic applications
- EDF & Areva: Value for nuclear applications
- IRSN: WP for nuclear applications
- Bureau Veritas: normative activities and Frama-Clang
- TrustInSoft and their customers: Value and Frama-Clang for security applications
- Dassault Aviation: home-made plug-ins + Value + Slicing + E-ACSL for security counter-measures
- Mitsubishi Electric: experimenting PathCrawler
- ...