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Software Analyzers

Runtime Assertion Checking with Frama-C

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DE LA RECHERCHE À L'INDUSTRIE
cea list

Runtime Verification 2013 Tutorial

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Motivation

Runtime verification of
rigorous, mathematical semantic properties of a C program

- safety properties:
  - no division by zero
  - no arithmetic overflow
  - validity of memory accesses
  - ...
- functional properties:
  - function preconditions must be satisfied by the caller
  - function postconditions must be satisfied by the callee
  - ...
- ...

Our goal

In this tutorial, we will see:

- how to specify a C program with the E-ACSL specification language
- how to detect errors at runtime with the E-ACSL plug-in of Frama-C
- how to customize the runtime verification
- how to combine runtime verification with other analyses

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Presentation of Frama-C

- Context
- Frama-C Overview
- ACSL and E-ACSL
- First Steps

Runtime Verification

- Checking Assertions
- Function Contract
- Integers
- Errors in Annotations
- Memory-Related Annotations

Customization

- Runtime Monitor Behavior
- Incomplete Program

Combinations with Other Analyzers

- Generating Annotations Automatically
- Mixing Static Verification and Runtime Assertion Checking

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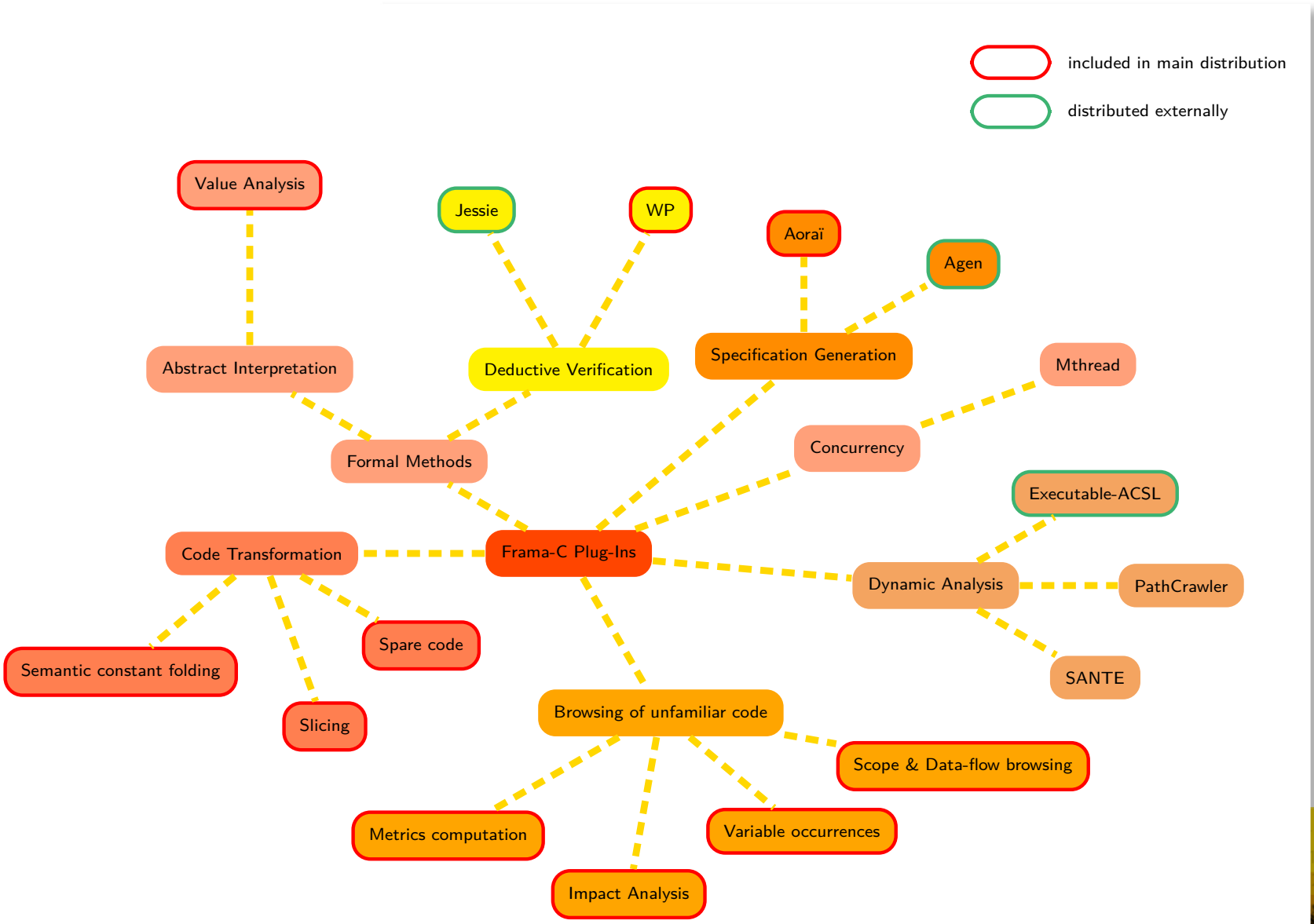
A brief history

- 90's: CAVEAT, an Hoare logic-based tool for C programs 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
- 2006: Joint project to write a successor to CAVEAT and Caduceus
- 2008: First public release of Frama-C (Hydrogen)
- today:
  - Frama-C Fluorine (v9)
  - Multiple projects around the platform
  - A growing community of users
  - and of plug-ins developers
  - Trust-In-Soft, startup based on Frama-C technologies

Frama-C at a glance

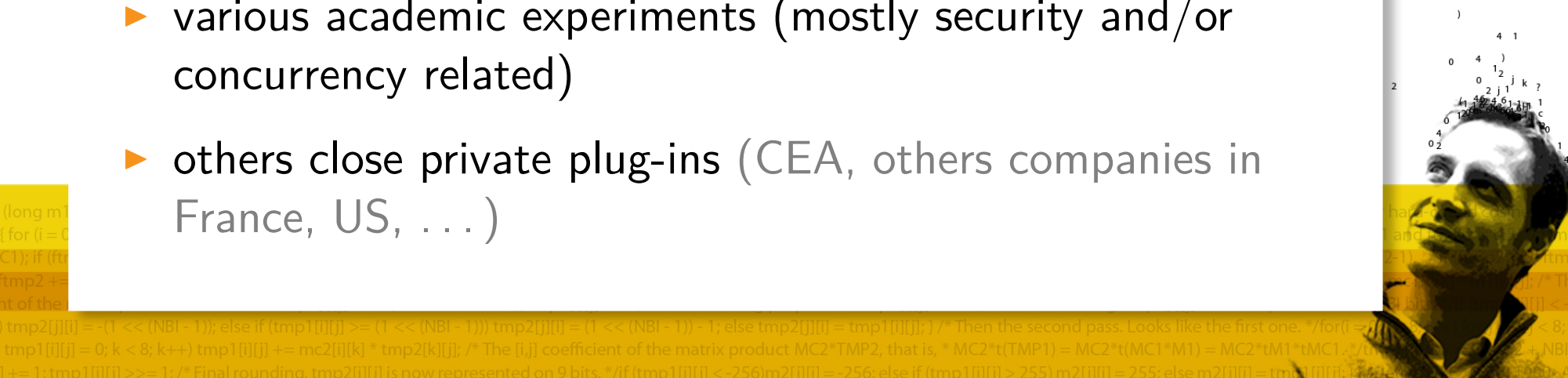
- A framework for modular analysis of C code.
- http://frama-c.com
- Developed at CEA LIST (Software Safety labs) and INRIA Saclay (Toccata team).
- Released under LGPL license (Fluorine v3 in June 2013)
- Kernel based on CIL (Necula et al. at Berkeley).
- ACSL annotation language.
- Extensible platform
  - Collaboration of analyses over same code
  - Inter plug-in communication through ACSL formulae.
  - Adding specialized plug-ins is easy

Main plug-ins



External plugins

- Dassault's internal plug-ins [Pariente & Ledinot, FoVeOOs 2010]
- Taster: coding rules (Atos/Airbus) [Delmas & *al.*, ERTSS 2010]
- Fan-C: flow dependencies (Atos/Airbus) [Duprat & *al.*, ERTSS 2012]
- simple Concurrency plug-in (Adelard) [first release in 2013]
- various academic experiments (mostly security and/or concurrency related)
- others close private plug-ins (CEA, others companies in France, US, . . .)



ACSL: ANSI/ISO C Specification Language

Presentation

- like JML or Spec# for C programs
- based on Eiffel-like contracts
- allows the users to specify functional properties of their programs
- designed for static analyzers
- already used in large-scale industrial projects
- allows communication between various plugins
- independent from a particular analysis
- ACSL manual at `http://frama-c.com/acsl`

- first-order logic
- pure C expressions (side-effect-free 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)`
  - `...`

E-ACSL: Executable-ACSL

E-ACSL, a specification language

- (large) executable subset of ACSL
- annotations may be evaluated at runtime

Differences with ACSL:

- few restrictions
- compatible semantics changes
- manual at `frama-c.com/download/e-acsl/e-acsl.pdf`

E-ACSL: Executable-ACSL

Benefits

Benefits:

- being executable allows to be understandable by dynamic tools (testing tools, monitors)
- being based on ACSL allows to be supported by existing Frama-C analyzers
- being translatable into C allows to be supported by other analysis tools for C

E-ACSL plug-in

E-ACSL, a Frama-C plug-in

- converts an annotated C program p into another one p'
- p' fails at runtime whenever an annotation is violated
- p' and p have the same behavior if no annotation is violated

Installation

Frama-C

Linux:

- packages on Debian, Ubuntu, Fedora, ...
- compile from sources using OCaml package managers:
  - Godi: `http://godi.camlcity.org/godi/index.html`
  - Opam: `http://opam.ocamlpro.com/`

Windows:

- Godi
- Wodi: `http://wodi.forge.ocamlcore.org/`

Mac OS X:

- Binary package available
- Source compilation through homebrew

Installation

E-ACSL

- this tutorial is mainly based on E-ACSL
- E-ACSL is a CEA's external Frama-C plug-in
- compile sources once Frama-C is installed
- `http://frama-c.com/download/e-acsl/e-acsl-0.3.tar.gz`

in this tutorial:
Frama-C Fluorine-20130601 + E-ACSL 0.3

Installed files

Executables

- `frama-c`: console-based interface
- `frama-c-gui`: Graphical User Interface

Testing the installation

- `frama-c -help`: list of available plug-ins
- `frama-c -kernel-help`: options provided by the kernel
- `frama-c -e-acsl-help`: E-ACSL specific options

Documentation

Manuals

- `http://frama-c.com/support.html`
- E-ACSL webpage: `http://frama-c.com/eacsl.html`
- `` `frama-c -print-share-path`/manuals ``
- `man frama-c`
- inline help
  - `frama-c -kernel-help`
  - `frama-c -`*`plugin`*`-help`

Support

- `frama-c-discuss@gforge.inria.fr`
- tag `frama-c` on `http://stackoverflow.com`

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Assertions

What and why?

- ensure properties at some program points
- defensive programming

How?

- C macro `assert` provided by `assert.h`
  - takes a C expression of type `int` as argument
- E-ACSL clause `assert`
  - takes an E-ACSL predicate as argument
  - much more expressive than C "boolean" expressions

Example 1: max

goal: check each value of `m` in function `main`.

```
int max(int x, int y) {  return x<y ? x : y; }

int main(void) {
  int m = max(0, 0);
  m = max(-4, 3);
  return 0;
}
```

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Example 1: max

Solution 1: use C assertions

```
#include <assert.h>

int max(int x, int y) { return x<y ? x : y; }

int main(void) {
  int m = max(0, 0);
  assert(m == 0);
  m = max(-4, 3);
  assert(m == 3);
  return 0;
}
```

Example 1: max

Solution 2: use E-ACSL assertions

```
int max(int x, int y) { return x<y ? x : y; }

int main(void) {
  int m = max(0, 0);
  /*@ assert m == 0; */
  m = max(-4, 3);
  /*@ assert m == 3; */
  return 0;
}
```

- generate the C code in file `a.c` with:

```
frama-c -e-acsl max_e_acsl_assert.c \
        -then-on e-acsl -print -ocode a.c
```

Function Contract

Principle

- goal: specification of imperative functions
- approach: give assertions (i.e. properties) about the functions
  - precondition is supposed to be true on entry (ensured by callers of the function)
  - postcondition must be true on exit (ensured by the function if it terminates)
- nothing is guaranteed when the precondition is not satisfied
- termination may or may not be guaranteed (total or partial correctness)

Function Contract

E-ACSL Plug-in

- the precondition is verified when entering the function
- the postcondition is verified when exiting the function
- the contract is thus verified for each function call

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Example 2: absval

goal:

specify function `absval` which computes the absolute value of its argument.

```
int absval(int x) { return x>0 ? x : -x; }
```

Example 2: absval

Solution

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

- that is actually wrong when the argument is `INT_MIN`.

Example 2: absval

Solution, fixed

```
#include <limits.h>

/*@ requires x > INT_MIN;
  @ ensures (x >= 0 ==> \result == x)
  @         && (x <  0 ==> \result == -x); */
int absval(int x) { return x>0 ? x : -x; }
```

- preprocessing annotations requires to use the option `-pp-annot`

Behaviors

- Global precondition (**`requires`**) and postcondition (**`ensures`**) apply to all cases
- Behaviors refine global contract in particular cases
- For each **`behavior`** (case):
  - the subdomain is defined by **`assumes`** clause
  - additional constraints are given with local **`requires`** clauses
  - the behavior's postcondition is defined by **`ensures`** clauses, 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 2: absval

Solution, improved

```
#include <limits.h>

/*@ requires x > INT_MIN;
  @ behavior pos:
  @   assumes x >= 0;
  @   ensures \result == x;
  @ behavior neg:
  @   assumes x < 0;
  @   ensures \result == -x;
  @ complete behaviors;
  @ disjoint behaviors; */
int absval(int x) { return x>0 ? x : -x; }
```

Integers

Specification language

- ACSL and E-ACSL use mathematical integers
- 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
- yet runtime computations may be more difficult

Integers

E-ACSL plug-in

- E-ACSL uses GMP to represent mathematical integers
- try to avoid them as much as possible (interval-based type system)
- no GMP in the previous examples
- indeed few GMP's in practice
- only used when the annotations talk about (potentially) very big integers
- in such a case, the generated code must be linked against GMP

Integers

Example

```
/*@ ensures \result > 0; */
unsigned long long my_pow
  (unsigned int x, unsigned int n)
{
  unsigned long long res = 1;
  while (n) {
    if (n & 1) res *= x;
    n >>= 1;
    x *= x;
  }
  return res;
}
```

- the generated program does not require GMP

Integers

Example, follow-up

```
/*@ ensures \result > 0;
  @ behavior two:
  @   assumes n == 2;
  @   ensures \result % n == 0;
  @   ensures (\result + 1) % n == 1; */
unsigned long long my_pow
  (unsigned int x, unsigned int n);
```

- the generated program requires GMP

Errors 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 `&&`, `||`, `_?_:_`, `==>`
  - correspond to Chalin's Runtime Assertion Checking semantics
  - consistent with ACSL: valid (resp. invalid) E-ACSL predicates remain valid (resp. invalid) in ACSL

Example 3: dividable

goal: specify the following function

```
int is_dividable(int x, int y) {
  return x % y == 0;
}
```

Example 3: dividable

Solution

```
/*@ behavior yes:
  @   assumes x % y == 0;
  @   ensures \result == 1;
  @ behavior no:
  @   assumes x % y != 0;
  @   ensures \result == 0; */
int is_dividable(int x, int y) {
  return x % y == 0;
}
```

- `x % y` may be undefined
- if undefined, E-ACSL prevents its execution by reporting an error

Example 3: dividable

Solution, improved

```
/*@ requires y != 0;
  @ behavior yes:
  @   assumes x % y == 0;
  @   ensures \result == 1;
  @ behavior no:
  @   assumes x % y != 0;
  @   ensures \result == 0; */
int is_dividable(int x, int y) {
  return x % y == 0;
}
```

- adding an extra annotation is usually better
- make the requirement explicit

Pointers

- E-ACSL provides several built-in predicates to talk about pointers
- `\valid(p)`: is p valid?
- `\initialized(p)`: is $*p$ initialized?
- `\base_addr(p)`: base address of the block containing p
- `\block_length(p)`: length of the block containing p
- `\offset(p)`: offset of p from `base_addr(p)`

Refering to another state

- specification may require values at different program points
- `\at(e,L)` refers to the value of expression `e` at label `L`
- some predefined labels:
  - `\at(e,Here)` refers to the current state
  - `\at(e,Old)` refers to the pre-state
  - `\at(e,Post)` refers to the post-state
- `\old(e)` is equivalent to `\at(e,Old)`

Example 4: swap

goal: specify the following function which swaps its arguments

```
void swap(int *p, int *q) {
  int tmp = *q;
  *q = *p;
  *p = tmp;
}
```

Example 4: swap

Solution

```
/*@ requires \valid(p);
  @ requires \valid(q);
  @ ensures *p == \old(*q);
  @ ensures *q == \old(*p); */
void swap(int *p, int *q) {
  int tmp = *q;
  *q = *p;
  *p = tmp;
}
```

- the generated code is machine-dependent: add `-machdep x86_64` on an x86-64 architecture
- the generated program must be linked against the E-ACSL memory library
- E-ACSL tries to minimize the instrumentation (dataflow analysis)

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Quantification

- E-ACSL is based on a first order logic
- it provides finite existential and universal quantifications over terms
- quantifications must be guarded

```
\forall τ x1,...,xn;
  a1 <= x1 <= b1 && ... && an <= xn <= bn
  ==> p

\exists τ x1,...,xn;
  a1 <= x1 <= b1 && ... && an <= xn <= bn
  && p
```

Example 5: sum of matrices

A more advanced example about pointers and quantification

goal: specify the following function which sums two square matrices

```
typedef int* matrix;
matrix sum(matrix a, matrix b, int size);
```

Example 5: sum of matrices

Solution

```
typedef int* matrix;

/*@ requires size >= 1;
  @ requires \forall integer i, j;
  @   0 <= i < size && 0 <= j < size ==>
  @   \valid(a+i*size+j) && \valid(b+i*size+j);
  @ ensures \forall integer i, j;
  @   0 <= i < size && 0 <= j < size ==>
  @   \valid(\result+i*size+j) &&
  @   \result[i*size+j] ==
  @     a[i*size+j]+b[i*size+j];
  @ */
matrix sum(matrix a, matrix b, int size);
```

Example 5: sum of matrices

Error detection

Which kind of error are we able to detect here?

- spatial error: invalid memory access due to out-of-bounds offset or array index
- temporal error: invalid memory access to a deallocated memory object
- memory leak: use more memory at the end of the execution than at the beginning.
  - use the special variable `__memory_size`

Loop Invariant

Definition

- clause `loop invariant` before a loop body
- indicates invariant properties in a loop
- a loop invariant is valid if and only if:
  - it holds before entering the loop
  - it holds at the end of the loop body, after each iteration
- necessary annotations for proof of programs with loops

Loop Invariant

Example

goals:

- specify the following function which searches an element `elt` in a sorted global array `A`
- provide loop invariants

```
int A[10];

int search(int elt) {
  int k;
  for(k = 0; k < 10; k++)
    if(A[k] == elt) return 1;
    else if(A[k] > elt) return 0;
  return 0;
}
```

Loop Invariant

Solution, part 1

```
int A[10];

/*@ requires \forall integer i;
  @     0 <= i < 9 ==> A[i] <= A[i+1];
  @  behavior exists:
  @    assumes \exists integer j;
  @       0 <= j < 10 && A[j] == elt;
  @    ensures \result == 1;
  @  behavior not_exists:
  @    assumes \forall integer j;
  @       0 <= j < 10 ==> A[j] != elt;
  @    ensures \result == 0; */
int search(int elt);
```

Loop Invariant

Solution, part 2

```
#include "linear_search_spec.c"

int search(int elt) {
  int k;
  /*@ loop invariant 0 <= k <= 10;
    @ loop invariant \forall integer i;
    @    0 <= i < k ==> A[i] < elt; */
  for(k = 0; k < 10; k++)
    if(A[k] == elt) return 1;
    else if(A[k] > elt) return 0;
  return 0;
}
```

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Runtime Monitor Behavior

- E-ACSL calls the function `e_acsl_assert` for each annotation
- by default, this function fails iff the input boolean expression corresponding to the annotation is false (i.e. 0)
- a failure generates an error message and aborts the execution
- possible to customize the behavior of the generated code by providing its own definition of `e_acsl_assert`

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Default Monitor Behavior

```
#include <stdlib.h>
#include <stdio.h>

void e_acsl_assert
   (int predicate, char *kind, char *fct,
    char *pred_txt, int line)
{
  if (! predicate) {
    printf(
      "%s failed at line %d in function %s.\n\
The failing predicate is:\n%s.\n",
       kind, line, fct, pred_txt);
    exit(1);
  }
}
```

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Custom Monitor Behavior

Invalid Predicate Tracker

```
#include <stdio.h>
void e_acsl_assert
   (int predicate, char *kind, char *fct,
    char *pred_txt, int line)
{
  if (! predicate) {
    FILE *f = fopen("logfile.log", "a");
    fprintf(
      f,
      "%s failed at line %d in function %s.\n\
The failing predicate is:\n%s.\n",
      kind, line, fct, pred_txt);
    fclose(f);
  }
}
```

Incomplete Program

- possible to run E-ACSL on code without a `main` (e.g. library) or containing undefined functions
- correct only if there is no memory-related annotations
- BE CAREFUL with memory-related annotations:
  - may need the option `-e-acsl-full-mmodel` for correctness
  - less efficient generated code
  - if no main is provided, may need to call `__e_acsl_memory_init` (resp. `__e_acsl_memory_clean`) at the beginning (resp. at the end) of the main before linking

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Generating Annotations Automatically

- Frama-C plug-ins may generate annotations
- the RTE plug-in generates an annotation for each potential runtime error
- possible to run RTE, then to run E-ACSL
- automatic detection of each runtime error
- option `-e-acsl-prepare` must be used in case of running an analysis before E-ACSL

Generating Annotations Automatically

Example

again the example of sum of matrices:
no need of writing assertions since RTE generates them

```
int main(void) {
  int a[] = { 1, 1, 1, 1 };
  int b[] = { 2, 2, 2, 2 };
  matrix c = sum(a, b, 2);
  free(c);
  //  /*@ assert \valid(&c[0]); */
  //  /*@ assert \valid(&c[2]); */
  int trace = c[0] + c[2];
  return 0;
}
```

Verifying Annotations Statically

- Frama-C comes with various static analyzers
- some aim at statically verifying a program
  - may guarantee the absence of runtime error
  - may ensure that a program satisfies its ACSL specification
- usually require extra work by the user
  - adding extra annotations
  - parameterizing the tool
  - writing stubs
- what to do when all the code is not statically verified?

may also use E-ACSL on such cases

Plug-in Wp

- based on Dijkstra's weakest preconditon calculus
- generates theorems (proof obligations) to ensure that a code satisfies its ACSL specification
- uses automatic/interactive theorem provers to verify these theorems
- is able to verify complex specifications
- requires to manually add extra annotations (e.g. loop invariants)

Mixing E-ACSL and Wp

Main ideas

- idea 1: dynamically check with E-ACSL the properties which are not statically proved with Wp.
- idea 2: use E-ACSL to test your specification before trying to prove it with Wp
  - use pre-existing test suites
  - write test cases manually
  - generate test cases with an automatic test generation tool like the PathCrawler plug-in of Frama-C
- the annotations proved by Wp are not converted by E-ACSL and so not checked at runtime (except if the option `-e-acsl-valid` is set)
- must use `-e-acsl-prepare` when running Wp

Mixing E-ACSL and WP

Example

goal: formally specify `binary_search` according to its informal specification

```
/* Takes as input a sorted array, its length,
   and an int to search for.
   Returns the index of a cell which contains
   the searched value.
   Returns -1 if the key is not present in the
   array. */
int binary_search(int *a, int length, int key);
```

Plugin Value

- based on Cousot's abstract interpretation
- computes over-approximations of possible values of variables at each program point
- evaluates simple E-ACSL annotations
- is able to statically ensure the absence of RTE
- generates extra E-ACSL annotations when it cannot guarantee the absence of RTE

Mixing altogether

- possible to combine Value, WP + E-ACSL
- even possible to send E-ACSL results back into Frama-C

Time for the final demo!

Conclusion

We have seen:

- how to specify a C program with the E-ACSL specification language
- how to detect errors at runtime with the E-ACSL plug-in of Frama-C
- how to customize E-ACSL
- how to combine E-ACSL with other analyses
  - RTE
  - WP
  - Value
  - PathCrawler

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