Frama-C Training Session
Introduction to ACSL and its GUI

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CEA List

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outline

- Presentation
- ACSL Specifications
  - Function contracts
  - First-order logic
  - Loops
  - Assertions
- Deductive Verification
  - Hoare logic
  - Pointers and Memory
  - Jessie Plugin

- Presentation
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Motivations

Main objective

Statically determine some semantic properties of a program

- safety: pointer are all valid, no arithmetic overflow, …
- termination
- functional properties
- dead code
- …

Embedded code

- Much simpler than desktop applications
- Some parts are critical, *i.e.* a bug have severe consequences (financial loss, or even dead people)
- Thus a good target for static analysis

Some tools

Polyspace Verifier	Checks for (absence of) run-time error C/C++/Ada) `http://www.mathworks.com/products/polyspace/`
ASTRÉE	Absence of error *without false alarm* in SCADE-generated code `http://www.di.ens.fr/~cousot/projets/ASTREE/`
Coverity	Checks for various code defects (C/C++/Java) `http://www.coverity.com`

Some tools (cont'd)

a3	Worst-case execution time and Stack depth `http://www.absint.com/`
FLUCTUAT	Accuracy of floating-point computations and origin of rounding errors `http://www-list.cea.fr/labos/fr/LSL/fluctuat/`
Frama-C	A toolbox for analysis of C programs `http://frama-c.com/`

A brief history

- 90's: CAVEAT, an Hoare logic-based tool for C programs
- 2000's: CAVEAT used by Airbus during certification process of the A380
- 2002: Why and its C front-end Caduceus
- 2006: Joint project to write a successor to CAVEAT and Caduceus
- 2008: First public release of Frama-C (Hydrogen)
- today:
  - Frama-C Boron
  - Multiple projects around the platform
  - A growing community of users

Architecture

- A modular architecture
- Kernel:
  - CIL (U. Berkeley) library for the C front-end
  - ACSL front-end
  - Global management of analyzer's state
- Various plug-ins for the analysis
  - Value analysis (abstract interpretation)
  - Jessie (translation to Why)
  - Slicing
  - Impact analysis
  - ...

ACSL: ANSI/ISO C Specification Language

Presentation

- Based on the notion of contract, à la Eiffel
- Allow the users to specify functional properties of their programs
- Allow communication between the various plugin
- Independent from a particular analysis

Basic Components

- 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)`,...

Presentation

ACSL Specifications

- Function contracts
- First-order logic
- Loops
- Assertions

Deductive Verification

- Hoare logic
- Pointers and Memory
- Jessie Plugin

Key Ingredients

Specification of a function

- Contract between caller and callee
- Callee **requires** some pre-conditions from the caller
- Callee **ensures** some post-conditions hold when it returns

A first example

```
unsigned int M;
/*@
  requires \valid(p) && \valid(q);
  ensures M == (*p + *q) / 2;
*/
void mean(unsigned int* p, unsigned int* q) {
  if (*p >= *q) { M = (*p - *q) / 2 + *q; }
  else { M = (*q - *p) / 2 + *p; }
}
```

Specification of Side Effects

The specification

```
/*@
  requires \valid(p) && \valid(q);
  ensures M == (*p + *q) / 2;

*/
void mean(unsigned int* p, unsigned int* q);
```

A valid implementation

Specification of Side Effects

The specification

```
/*@
  requires \valid(p) && \valid(q);
  ensures M == (*p + *q) / 2;

*/
void mean(unsigned int* p, unsigned int* q);
```

A valid implementation

```
void mean(int *p, int* q)
{
  *p = *q = M = 0;
}
```

Specification of Side Effects

The specification

```
/*@
  requires \valid(p) && \valid(q);
  ensures M == (*p + *q) / 2;
  ensures *p == \old(*p) && *q == \old(*q);
*/
void mean(unsigned int* p, unsigned int* q);
```

A valid implementation

Specification of Side Effects

The specification

```
/*@
  requires \valid(p) && \valid(q);
  ensures M == (*p + *q) / 2;
  ensures *p == \old(*p) && *q == \old(*q);
*/
void mean(unsigned int* p, unsigned int* q);
```

A valid implementation

```
int A = 42;
void mean(int *p, int* q) {
  if (*p >= *q) ... else ...
  A = 0; }
```

Specification of Side Effects

The specification

```
/*@
  requires \valid(p) && \valid(q);
  ensures M == (*p + *q) / 2;
  assigns M;
*/
void mean(unsigned int* p, unsigned int* q);
```

A valid implementation

Specification of Side Effects

The specification

```
/*@
   requires \valid(p) && \valid(q);
   ensures M == (*p + *q) / 2;
   assigns M;
*/
void mean(unsigned int* p, unsigned int* q);
```

A valid implementation

```
void mean(int *p, int* q) {
   if (*p >= *q) { M = (*p - *q) / 2 + *q; }
   else { M = (*q - *p) / 2 + *p; }
}
```

A more advanced example

Informal spec

- Input: a sorted array and its length, an element to search.
- Output: index of the element or −1 if not found

Towards a formal specification

```
int find_array(int* arr, int length, int query);
```

- How to specify the two distinct outcome?
- What does that mean for `arr` to be `sorted`?
- How to prove the implementation?

Deductive Verification

Behaviors

```
/*@ behavior found:
  assumes \exists integer i;
    0<=i<length && arr[i] == query;
  ensures 0<=\result<length &&
          arr[\result] == query;
 behavior not_found:
  assumes \forall integer i;
    0<=i<length ==> arr[i] != query;
  ensures \result == -1;
 complete behaviors; disjoint behaviors;
*/
int find_array(int* arr, int length, int query);
```

Predicate definition

```
/*@
predicate sorted{L}(int* arr, int length) =
  \forall integer i,j;
     0<=i<=j<length ==> arr[i] <= arr[j];
*/

/*@ requires sorted{Here}(arr,length);
    requires \valid(arr+(0..length-1));
    requires length >= 0;
*/
int find_array(int* arr, int length, int query);
```

Axiomatic definition

```
/*@
inductive sorted{L}(int* arr, int length) {
  case singleton{L}:
    \forall int* arr; sorted{L}(arr,0);
  case trans{L}:
    \forall int* arr, integer length;
    sorted{L}(arr,length)
    && arr[length-1] <= arr[length]
    ==> sorted{L}(arr,length + 1);
} */

/*@ requires sorted{Here}(arr,length);
    requires \valid(arr+(0..length-1));
    requires length >= 0;
*/
int find_array(int* arr, int length, int query);
```

Implementation of `find_array`

```
int find_array(int* arr, int length, int query)
{
  int min = 0;
  int max = length - 1;
  int mean;
  while (min <= max) {
    mean = min + (max - min) / 2;
    if (arr[mean] == query) return mean;
    if (arr[mean] < query)
      min = mean + 1;
    else
      max = mean - 1;
  }
  return -1;
}
```

Loop annotations

```
/*@ loop invariant 0<= min < length;
    loop invariant 0<= max < length;
    loop invariant
      \forall integer i;
         0<=i<min ==> arr[i] < query;
    loop invariant
      \forall integer i;
         max<i<length ==> arr[i] > query;
    loop assigns mean, min, max;
    loop variant max - min;
*/
  while (min <= max) { ... }
```

```
while (min <= max) {
  mean = min + (max - min) / 2;
  /*@ assert min <= mean <= max; */
  if (arr[mean] == query) return mean;
  if (arr[mean] < query)
    min = mean + 1;
  else
    max = mean - 1;
```

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Hoare logic

- Introduced by Floyd and Hoare (70s)
- Hoare triple: $\{P\}s\{Q\}$, meaning: *If P holds, then Q will hold after the execution of statement s*
- Deduction rules on Hoare triples: *Axiomatic semantic*

Some rule examples

$$\frac{}{\{P\}\{P\}} \qquad \frac{P \Rightarrow P' \qquad \{P'\}\mathsf{s}\{Q'\} \qquad Q' \Rightarrow Q}{\{P\}\mathsf{s}\{Q\}}$$

$$\frac{\{P\}\mathsf{s\_1}\{R\} \qquad \{R\}\mathsf{s\_2}\{Q\}}{\{P\}\mathsf{s\_1;s\_2}\{Q\}} \qquad \frac{e \text{ evaluates without error}}{\{P[x \leftarrow e]\}\mathsf{x{=}e;}\{P\}}$$

$$\frac{\{P \wedge \mathsf{e}\}\mathsf{s\_1}\{Q\} \qquad \{P \wedge \mathsf{!e}\}\mathsf{s\_2}\{Q\}}{\{P\}\ \textsf{if}\ \ (\mathsf{e})\ \ \mathsf{s\_1}\ \textsf{else}\ \ \mathsf{s\_2}\{Q\}}$$

$$\frac{\{I \wedge \mathsf{e}\}\mathsf{s}\{I\}}{\{I\}\textsf{while}\ \ (\mathsf{e})\ \ \mathsf{s}\{I \wedge \mathsf{!e}\}}$$

Weakest pre-condition

- Program seen as a predicate transformer
- Given a function s, a pre-condition Pre and a post-condition $Post$
- We start from $Post$ at the end of the function and go backwards
- At each step, we have a property Q and a statement s, and compute the *weakest pre-condition* P such that $\{P\}s\{Q\}$ is a valid Hoare triple.
- When we reach the beginning of the function with property P, we must prove $Pre \Rightarrow P$.

Some rules

- Assignment

$$WP(\mathsf{x{=}e}, Q) = Q[\mathsf{x} \leftarrow \mathsf{e}]$$

- Sequence

$$WP(\mathsf{s\_1;s\_2}, Q) = WP(\mathsf{s\_1}, WP(\mathsf{s\_2}, Q))$$

- Conditional

$$\begin{aligned} WP(\textbf{if}\ \ (\mathsf{e})\ \ \mathsf{s\_1}\ \textbf{else}\ \ \mathsf{s\_2}, Q) \quad &= \\ \mathsf{e} \Rightarrow WP(\mathsf{s\_1}, Q) \wedge\, !\mathsf{e} \Rightarrow WP(\mathsf{s\_2}, Q) & \end{aligned}$$

- While

$$\begin{aligned} WP(\textbf{while}\ \ (\mathsf{e})\ \ \mathsf{s}, Q) \quad &= \\ I \wedge \forall\omega.I \Rightarrow (\mathsf{e} \Rightarrow WP(\mathsf{s}, I) \wedge\, !\mathsf{e} \Rightarrow Q) & \end{aligned}$$

Memory Model

Issue

How can we represent memory operations (`*x`, `a[i]=42`,...) in the logic

- If too low-level (a big array of bytes), proof obligations are intractable.
- If too abstract, some C constructions can not be represented (arbitrary pointer casts, aliasing)
- Standard solution (Burstal-Bornat): replace struct's components by a function

Aliasing

Issue

The same memory location can be accessed through different means:

```
int y;
int* yptr = &y;
*yptr = 3;
/*@ assert y == 3; */
```

- Again, supposing that any two pointers can be aliases would lead to intractable proof obligations.
- Memory is separated in disjoint regions
- Some hypotheses are done (as additional pre-conditions)

What is Jessie?

- Hoare-logic based plugin, developed at INRIA Saclay.
- Input: a program and a specification
- Jessie generates verification conditions
- Use of Automated Theorem Provers to discharge the VCs
- If all VCs are proved, the program is correct with respect to the specification
- Otherwise: need to investigate why the proof fails
    - Fix bug in the code
    - Adds additional annotations to help ATP
    - Interactive Proof (Coq/Isabelle)

What is Jessie Useful for?

Usage

- Proof of functional properties of the program
- Modular verification (function per function)

Limitations

- Cast between pointers and integers
- Limited support for union type
- Aliasing requires some care

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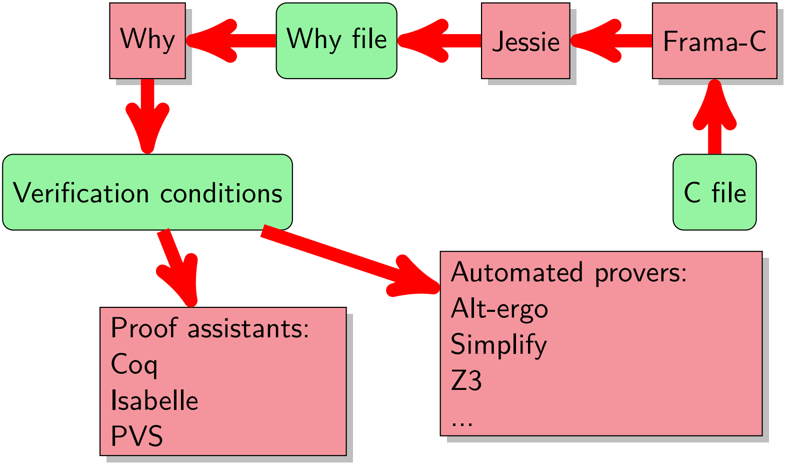
From Frama-C to Theorem Provers



Why

Why file

Jessie

Frama-C

C file

Verification conditions

Proof assistants:
Coq
Isabelle
PVS

Automated provers:
Alt-ergo
Simplify
Z3
...

In practice

- Launch GUI:

```
frama-c -jessie file.c
```

- Batch processing with alt-ergo:

```
frama-c -jessie -jessie-atp alt-ergo file.c
```

- Generate Coq file (to be completed interactively):

```
frama-c -jessie -jessie-atp coq file.c
```

- Concentrate on functional properties:

```
frama-c -jessie -jessie-behavior default file.c
```

- Concentrate on safety properties:

```
frama-c -jessie -jessie-behavior safety file.c
```