Deductive Verification in Frama-C and SPARK2014: Past, Present and Future

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OSIS, Frama-C & SPARK day, May 30th, 2017

Outline

Why this joint Frama-C and SPARK day?

- common history of Frama-C and SPARK

ACSL and SPARK 2014: how they differ?

- static versus runtime checking
- specification languages: design choices
- advertisement: ghost code

Recent and Future Trends

- bit-wise, floating-point computations
- proof debugging, counterexamples
- interactively discharging VCs

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Around 1990

Deductive Verification

- Formal Specification of functional behaviors using *contracts*
- Generation of *Verification Conditions*
- Computer-Assisted *Theorem Proving*

- *SPARK Examiner* for Ada'83
  - Univ. Southampton, Praxis, then Altran
  - home-made VC generator, simplifier, checker
- *CAVEAT*, static analyzer for C code
  - CEA
  - home-made VC generator and solver

Around 2000

- The *Why* tool for deductive verification
  - team ProVal (Inria & CNRS & Univ. Paris Sud)
  - a ML-style programming language with contracts
  - VC discharged using *Coq*
    - then later with *Simplify*
    - then with *Alt-Ergo*
    - then with several others

- Why front-ends:
  - for Java: *Krakatoa*
    - annotations $\simeq$ *Java Modeling Language*
  - for C: *Caduceus*
    - annotation language $\simeq$ JML

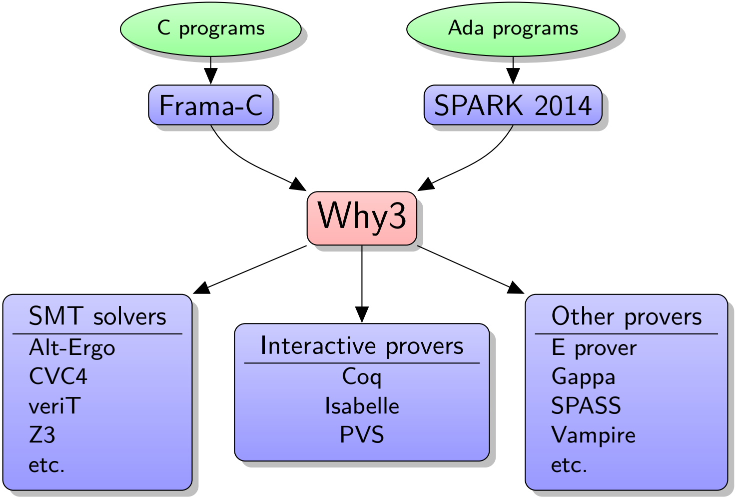
2005-2010

- *Frama-C*
  - CEA and ProVal
  - *ACSL* language
  - *plug-in architecture* to support various kind of analyses
- *Jessie*
  - Deductive Verification plug-in
  - Use Why as intermediate language
  - *Alias analysis* using memory regions

2010-2014

- *Why3*, new generation of Why
    - module system, rich standard library of theories
    - region-based type system for *alias control*
    - generic architecture to plug in back-end provers
- Jessie plug-in adapted to Why3
- *WP* Frama-C plug-in
    - various *memory models* and *aliasing conditions*
    - call provers through Why3
- *SPARK 2014*: SPARK new generation
    - AdaCore - Altran
    - Why3 as intermediate programming language
    - *Non-aliasing conditions* to ease VC generation and proof
    - call provers through Why3

Why3 'ecosystem' today



C programs

Ada programs

Frama-C

SPARK 2014

Why3

SMT solvers
- Alt-Ergo
- CVC4
- veriT
- Z3
- etc.

Interactive provers
- Coq
- Isabelle
- PVS

Other provers
- E prover
- Gappa
- SPASS
- Vampire
- etc.

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Static versus Runtime Checking

Contracts can be used either

- for *runtime assertion checking* (RAC):
  - assertions executed and checked valid during execution, tests
- for *static verification* (VC generation + theorem proving)
  - code can be proved correct w.r.t. contracts

Example: Java Modeling Language

- JML RAC: turns assertions into regular Java code
- Static verification: *ESC/Java*, using solver *Simplify*

From JML to Krakatoa and ACSL

- JML was designed with RAC in mind
- Consequence: assertions are *Java Boolean expressions*
- Extensions to Java expressions: meant to be *executable*
  - e.g. quantification must be bounded

```
(\forall int i; 0 <= i && i < a.length; P(i))
```

- Models for specifications can be designed using extra *pure* classes
  - methods need to be *terminating*
  - they *should not raise exceptions*
  - they *should not have side-effects*

Why3/Krakatoa/ACSL Specification Languages

- Specification language is classical first-order logic with
    - types (polymorphism)
    - equality, built-in arithmetic
    - user-defined theories to design *abstract models*
        - introducing new data-types, logic functions, predicates
        - either defined or axiomatized

Specification language

- *distinct* from programming language
- *adequate for use of external provers*
- *does not need to be executable*

Example: sorting algorithms

```
/*@ requires \valid(a+(0..n-1));
  @ assigns a[0..n-1];
  @ ensures sorted(a,0,n);
  @ ensures permut{Pre,Post}(a,0,n-1);
  @*/
void sort(int *a, int n) {
```

Example: sorting algorithms

```
/*@ predicate sorted(int *a, integer l, integer h) =
  @  \forall integer i j; l <= i <= j < h ==> a[i] <= a[j] ;
  @*/
```

- Not executable *a priori*
- Could be executed if ranges of i and j are somehow 'computed'
  - In JML, it should be written

```
(\forall int i; l <= i && i < h ;
  (\forall int j; i <= j && j < h; a[i] <= a[j])) ;
```

- Notice also the type `integer` for mathematical, unbounded integers

Example: sorting algorithms

```
/*@ predicate swap{L1,L2}(int *a, integer i, integer j) =
  @  \at(a[i],L1) == \at(a[j],L2) && \at(a[j],L1) == \at(a[i],L2) &&
  @  \forall integer k; k != i && k != j ==> \at(a[k],L1) == \at(a[k],L2);
  @
  @ inductive permut{L1,L2}(int *a, integer l, integer h) {
  @ case permut_refl{L}:
  @  \forall int *a, integer l h;   permut{L,L}(a, l, h) ;
  @ case permut_sym{L1,L2}:
  @  \forall int *a, integer l h;
  @   permut{L1,L2}(a, l, h) ==> permut{L2,L1}(a, l, h) ;
  @ case permut_trans{L1,L2,L3}:
  @  \forall int *a, integer l h;
  @   permut{L1,L2}(a, l, h) && permut{L2,L3}(a, l, h) ==> permut{L1,L3}(a, l, h);
  @ case permut_swap{L1,L2}:
  @  \forall int *a, integer l h i j;
  @    l <= i < h && l <= j < h && swap{L1,L2}(a, i, j) ==> permut{L1,L2}(a, l, h) ;
  @ }
  @*/
```

Important points

- Why3/ACSL spec. lang. significantly diverged from JML
- Spec. language can be more powerful when RAC is not intended
- Yet, RAC may be useful to complement proofs

Design of E-ACSL

E-ACSL:

- Need for run-time checking in Frama-C
- *Executable* subset of ACSL
- assertions turned into regular C code:
  - mathematical integers handled using GMP
  - built-in memory-related predicates (`\valid`, `\initialized`) handled using a specific memory management library
  - axiomatic models not supported

ACSL and E-ACSL have slightly different semantics

Undefined expressions:

```
assert { 1/0 == 1/0 }
assert { *p == *p }  // when p == NULL
```

- valid in ACSL (logic of *total functions*)
- raise errors in E-ACSL

Note: similar differences between JML RAC and ESC/Java

Ada contracts and SPARK 2014

Ada 2012:

- add *contracts as part of regular Ada*
- assertions are *Boolean expressions*
- Expression-functions can be used in assertions
- Bounded quantification now part of Ada expressions:

```
for all I in <range> => P(I)
```

- *Ada compiler generates corresponding run-time checks* for pre- and post-conditions

Static Verification in SPARK 2014

Important design choice

Semantics of annotations is fixed by the execution semantics

- VC are generated for well-definedness: $1/0$, array index in bounds, etc.
- abstract models, unbounded integers:
  - not possible since it would forbids RAC
  - indeed possible via an SPARK-specific extension (*"external axiomatization"*)

Summary

	Why3	Frama-C		SPARK
		ACSL	E-ACSL	2014
Executable contracts	no	no	yes	yes
Only total functions in logic	yes	yes	no[1]	no[2]
Unbounded integers in logic	yes	yes	yes	no[3]
Unbounded quantification	yes	yes	no	no
Ghost code	yes	yes[4]	yes[4]	yes

[1] run-time checks for well-definedness are generated

[2] run-time checks and VCs for well-definedness are generated

[3] possible through external axiomatization

[4] restrictions: only executable C code, and non-interference with regular code is not checked

(See [Kosmatov et al., ISOLA'2016] for more details)

Advertisement: be Afraid of no Ghost!

- *ghost variable*: added to the regular, for the purpose of formal specification
- *ghost code*, *subprograms*: extra code added to operate on ghost variables

Ghost code

Commonly used in most non-trivial examples

- keeping track of previous values of variables
- attach some abstract state (a kind of data refinement)
- etc.

Example: a sorting algorithm may return a ghost array of indices, giving the permutation of elements done by sorting.

```
procedure sort(a:array) returns (ghost p:array of integer)
  assigns a
  ensures \forall integer i; a[i]=\old(a)[p[i]]
```

Ghost code in Why3, Frama-C and SPARK 2014

Ghost code is possible in all of them

Pros

- Very useful in practice/for complex cases
- A kind of 'executable' specification
- *Compatible with both static and run-time checking*

Cons

Tools should check non-interference between ghost code and regular code

- Why3, SPARK 2014 do it thanks to *strong non-aliasing policy*
- Frama-C doesn't do it yet

Bonus: Lemma Functions

Proving theorems using ghost code!

```
ghost $f(x_1 : \tau_1, \ldots, x_n : \tau_n)$ returns $r : \tau$
  requires $Pre$
  ensures $Post$
```

if this function has *no side-effect* and is *proved terminating* then it is a constructive proof of

$$\forall x_1, \ldots, x_n, \exists r, Pre \Rightarrow Post$$

Examples:

- proving lemmas by induction (with automated provers only!)
- proving existential properties

Note: similar feature exists in other environments, e.g. Dafny

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The *ProofInUse* project

PROOF IN USE
SPARK-2014.ORG/PROOFINUSE

Joint Lab between Inria and AdaCore

Main Goal

Spread the use of formal proof in SPARK users' community

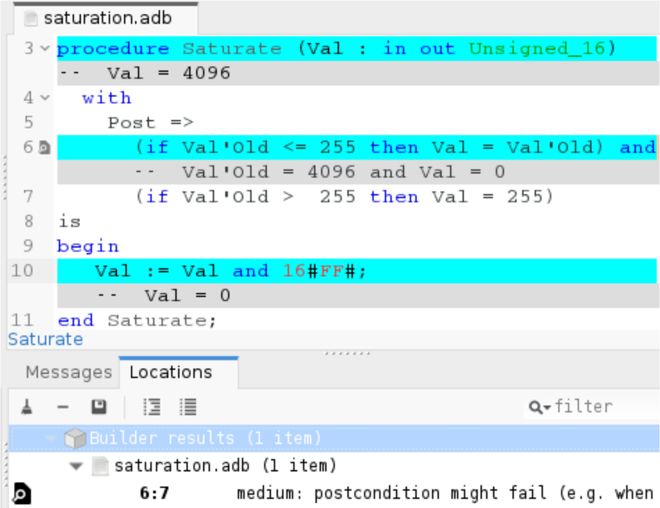
- Help for "debugging" when proof fails
  - Counterexamples
  - Simple interactive prover
- Enlarge language support
  - Bit-wise operators
  - Floating-point arithmetic
- Increase automation
  - Better exploit SMT solvers

Bit-Wise Operators

- New Why3 theory for bit-wise operations
- Use of *SMT-LIB bit-vector theory* (CVC4, Z3)
- Case study: *BitWalker*
  - Original C code by Siemens, ITEA 2 project OpenETCS
  - Rewritten by Jens Gerlach for Frama-C/WP
    - Formal specification in ACSL
    - proved with Alt-Ergo+Coq
  - Version in SPARK 2014
    - proved with Alt-Ergo+CVC4+Z3

See [Fumex et al., NFM'2016]

Counterexample Generation in SPARK



```
 3 procedure Saturate (Val : in out Unsigned_16)
   --   Val = 4096
 4   with
 5     Post =>
 6        (if Val'Old <= 255 then Val = Val'Old) and
          --   Val'Old = 4096 and Val = 0
 7        (if Val'Old >  255 then Val = 255)
 8 is
 9 begin
10    Val := Val and 16#FF#;
      --   Val = 0
11 end Saturate;
```

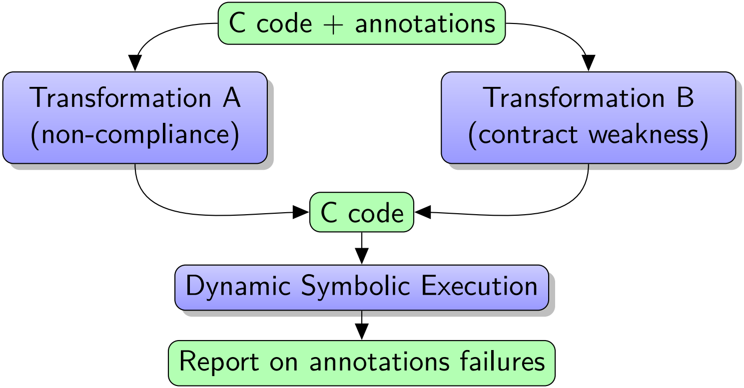
```
6:7      medium: postcondition might fail (e.g. when
```

Counterexample Generation in SPARK

- Instrumentation of VC generation for tracing variables
- Query a model when SMT solver answers 'SAT'
- Reinterpret the model in the source code
- Display counterexample in the graphical interface

See [Hauzar et al., SEFM'2016]

Proof Debugging (Frama-C plug-in StaDy)



C code + annotations

Transformation A (non-compliance)

Transformation B (contract weakness)

C code

Dynamic Symbolic Execution

Report on annotations failures

- Non-compliance: code does not satisfy annotations
- subcontract weakness:
  contracts of called functions, loop invariants, not powerful enough to prove the annotations correct

See [Petiot et al., TAP'2016]

Discharging VCs interactively

Goal

(hopefully simple) user interactions to assist automatic provers when proof fails

- On-going work for SPARK within ProofInUse joint lab
- Recently available in Frama-C/WP

See the talk by Loïc Correnson today!

Floating-Point Computations

Goals

- better handling Floating-Point in specifications and VC generation
- improve success rate of automated provers

- *SOPRANO* project
  - involves both Frama-C and SPARK developers
  - solvers Alt-Ergo FP and COLIBRI
- recent progress in SPARK
  - support for FP in SPARK 17.1, using
    - CodePeer interval analysis
    - FP support in prover Z3
  - on-going: use of Alt-Ergo FP and COLIBRI

See the talk by François Bobot today!

Conclusions

- Frama-C and SPARK share not only a common history but
  - A will to transfer academic research to the industry of critical software
  - Common challenges, approaches, technical solutions

OSIS Frama-C and SPARK day

Enjoy the talks, exchange ideas during breaks!