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Applications of Contracts for Security Certifications

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Tool context: ACSL, Frama-C and its deductive verification plugin WP

Frama-C is a platform for analysis and verification of C programs

- **ACSL (ANSI C Specification Language)** supported by Frama-C

WP plugin: Weakest Precondition based tool for deductive verification

- **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 **Why3** and **Automatic Theorem Provers** to discharge VCs
  - **Alt-Ergo**, Z3, CVC4, CVC5, …

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Example of 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 with Frama-C/WP

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Outline

- Motivation: Specification and verification of global (security) properties
- High-Level ACSL Requirements (HILARE), or Metaproperties, and MetAcsl tool
- Examples of Proof with MetAcsl and WP
- Application to certification of JavaCard Virtual Machine
- Relational properties
  - Specification and verification using self-composition
  - Verification using a VCGen: formalization and proof in Coq
- Conclusion and perspectives

Motivation: Why security properties are hard to specify and verify in Frama-C?

Integrity for some data area `data`: no satisfactory solutions:

`assigns \nothing;` or `assigns <what can be modified>;`

- Specifies that data area `data` ***cannot be modified by the function***
- **Does not work** if `data` can be modified only **under some condition** `cond` (access rights,…)

```
assigns data;
ensures !\old(cond)==> \at(data,Pre)== \at(data,Post);
```

- Specifies that data area `data` is unchanged ***after the function*** if `cond` was false
- It does not forbid **internal modifications inside the function** (risk of attack)
- What if `cond` **can be modified?**
- How to ensure that `data` **cannot be modified even temporarily inside the function**?

Confidentiality: no direct solution at all in Frama-C

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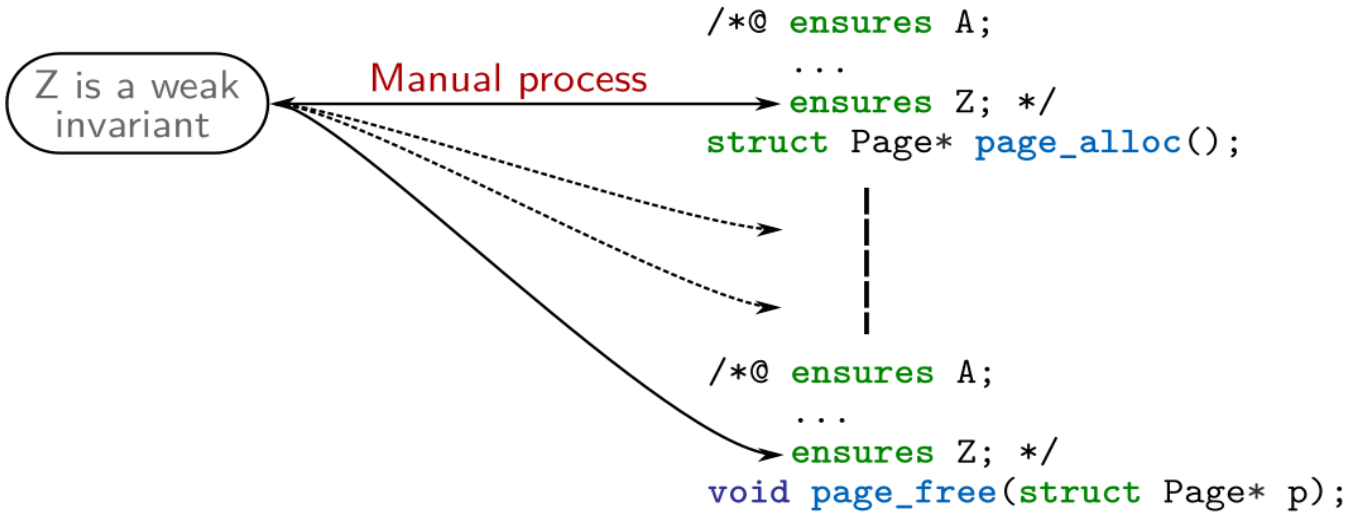
Motivation: Global (High-Level) properties are hard to specify and to maintain

Specifying global properties with contracts: manual and tedious. No explicit link between clauses.



Assessing if contracts form a global property is difficult, especially after an update.

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Examples of High-Level Properties

- A non-privileged user never reads a privileged (private) data page
- A privileged user never writes to a non-privileged (public) page
- The privilege level of a page cannot be changed unless...
- The privilege level of a user cannot be changed unless…
- A free page cannot be read or written, and must contain zeros
- Object data can be written only by the object owner
- Object data can be read only by the object owner

Such properties can be expressed as

- Constraints on reading / writing operations, calls to some functions,
- Strong or weak invariants

Solution: Metaproperties, or HILARE (High-Level ACSL Requirements)

We introduce meta-properties, which are a combination of:

- **A set of targets functions**, on which the property must hold.
  `foo` `{foo, bar}` `\ALL` `\diff(\ALL,{foo, bar})`
- **A context**, which characterizes the situation in which the property must hold.
  `\strong_invariant` `\writing` `\reading`
- **An ACSL predicate**, expressed over the set of global variables.
  `A < B` `*p == 0` `\separated(\written, p)`

```
meta \prop,
    \name(A < B everywhere in foo and bar),
    \targets({foo, bar}),
    \context(\strong_invariant),
    A < B;
```


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Available Contexts

- **Strong invariant:** Everywhere in the function
- **Weak invariant:** Before and after the function
- **Upon writing:** Whenever the memory is modified. The predicate can use a special meta-variable `\written`, referencing the address(es) being written to at a particular point.

```
meta \prop, \name(X is only modified if null),
       \targets(\ALL), \context(\writing),
       !\separated(\written, &X) ⇒ X == 0;
```

- **Upon reading:** Similarly, when memory is read
- **Upon calling:** Similarly, when a function is called

```
meta \prop, \name(foo can only be called from bar),
       \targets(\diff(\ALL, bar)),
       \context(\calling), \called ≠ &foo;
```

Example: Integrity Metaproperty Verified with MetAcsl – Writing context

Resulting code after generating assertions with MetAcsl and proof with Frama-C/WP:

```
/*@ meta "A_unchanged_unless";
  */
/*@ requires
    ensures
      (C ≥ 0
      (C < 0
    assigns A,
  */
void foo(voi
{
  if (C >= 0) {
    /*@ check A_unchanged_unless: _1: meta: C < 0 → \separated(&A, &A);
    A = C;
    /*@ check A_unchanged_unless: _2: meta: C < 0 → \separated(&B, &A);
    B = C;
  }
  return;
}
```

If all instances are proved, the metaproperty is true

MetAcsl

Contrary to an assert, a check is not kept in the proof context and does not overload the proof

MetAcsl instantiates a metaproperty in all relevant locations

Initial C code:

test5.c

```
1 int A, B, C;
2 /*@
3   meta \prop, \name(A_unchanged_unless),
4        \targets(\ALL), \context(\writing),
5   C < 0 ==> \separated(\written, &A);
6 */
7 /*@
8   requires A==B;
9   assigns A,B;
10  ensures C>=0 && A==C && B==C ||
11    C<0 && A==\old(A) && B==\old(B); */
12 void foo(){
13   if ( C >= 0 ){
14     A = C;
15     B = C;
16   }
```


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Example: Confidentiality Metaproperty Verified with MetAcsl – Reading context

Resulting code after generating assertions with MetAcsl and proof with Frama-C/WP:

```
/*@ meta "A_not_read";
*/
/*@ requires A ≡ B;
    ensures
      (C ≥ 0 ∧ A ≡ C ∧ B ≡ C) ∨
      (C < 0 ∧ A ≡ \old(A) ∧ B ≡ \old(B));
    assigns A, B;
 */
void foo(void)
{
  /*@ check A_not_read: _1: meta: \separated(&C, &A); */
  if (C >= 0) {
    /*@ check A_not_read: _2: meta: \separated(&C, &A); */
    A = C;
    /*@ check A_not_read: _3: meta: \separated(&C, &A); */
    B = C;
  }
  return;
}
```

MetAcsl

Initial C code:

test4.c

```
1 int A, B, C;
2 /*@
3   meta \prop, \name(A_not_read),
4     \targets(\ALL), \context(\reading),
5     \separated(\read, &A);
6 */
7 /*@
8   requires A==B;
9   assigns A,B;
10  ensures C>=0 && A==C && B==C ||
11    C<0 && A==\old(A) && B==\old(B); */
12 void foo(){
13   if ( C >= 0 ){
14     A = C;
15     B = C;
16   }
17 }
18
```


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Example: Strong Invariant

Resulting code after generating assertions with MetAcsl and proof with Frama-C/WP:

```
int A;
int B;
int C;
/*@ meta "A_B_eq_strong";
*/
/*@ check requires A_B_eq_strong: _1: meta: A ≡ B;
    requires A ≡ B;
    check ensures A_B_eq_strong: _1: meta: A ≡ B;
    ensures
      (C ≥ 0 ∧ A ≡ C ∧ B ≡ C) ∨
      (C < 0 ∧ A ≡ \old(A) ∧ B ≡ \old(B));
    assigns A, B;
 */
void foo(void)
{
  if (C >= 0) {
    A = C;
    /*@ check A_B_eq_strong: _3: meta: A ≡ B; */ ;
    B = C;
    /*@ check A_B_eq_strong: _4: meta: A ≡ B; */ ;
  }
  /*@ check A_B_eq_strong: _2: meta: A ≡ B; */ ;
  return;
  /*@ check A_B_eq_strong: _5: meta: A ≡ B; */ ;
}
```

Initial C code:

test2.c

```
1 int A, B, C;
2 /*@
3   meta \prop, \name(A_B_eq_strong),
4     \targets(\ALL), \context(\strong_invariant),
5     A == B;  // FAILS
6 */
7 /*@
8   requires A==B;
9   assigns A,B;
10  ensures C>=0 && A==C && B==C ||
11    C<0 && A==\old(A) && B==\old(B); */
12 void foo(){
13   if ( C >= 0 ){
14     A = C;
15     B = C;
16   }
17 }
18
```

Does not hold as a strong invariant betw. lines 14,15

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Example: Weak Invariant

Resulting code after generating assertions with MetAcsl and proof with Frama-C/WP:

```
int A;
int B;
int C;
/*@ meta "A_B_eq_weak";
*/
/*@ check requires A_B_eq_weak: _1: meta: A ≡ B;
    requires A ≡ B;
    check ensures A_B_eq_weak: _1: meta: A ≡ B;
    ensures
      (C ≥ 0 ∧ A ≡ C ∧ B ≡ C) ∨
      (C < 0 ∧ A ≡ \old(A) ∧ B ≡ \old(B));
    assigns A, B;
 */
void foo(void)
{
  if (C >= 0) {
    A = C;
    B = C;
  }
  return;
}
```

Initial C code:

test3.c

```
1 int A, B, C;
2 /*@
3   meta \prop, \name(A_B_eq_weak),
4     \targets(\ALL), \context(\weak_invariant),
5     A == B;
6 */
7 /*@
8   requires A==B;
9   assigns A,B;
10  ensures C>=0 && A==C && B==C ||
11    C<0 && A==\old(A) && B==\old(B); */
12 void foo(){
13   if ( C >= 0 ){
14     A = C;
15     B = C;
16   }
17 }
18
```

Holds as a weak invariant

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Examples of HILAREs

```
meta \prop, \name(Do not write to lower pages outside free),
  \targets(\diff(\ALL , {page_free})),
  \context( \writing ),

  \forall integer i; 0 <= i < MAX_PAGE_NB ==>
  \let p = pages + i;
  p->status == PAGE_ALLOCATED &&
  user_level > p->confidentiality_level ==>
  \separated(\written, p->data + (0.. PAGE_SIZE - 1));

meta \prop, \name(Free pages are never read),
  \targets(\ALL),
  \context( \reading ),

  \forall integer i; 0 <= i < MAX_PAGE_NB &&
  pages[i].status == PAGE_FREE ==>
  \separated(\read, pages[i].data + (0 .. PAGE_SIZE - 1));
```

Application to certification of JavaCard Virtual Machine

- Common Criteria Certification
- JavaCard Virtual Machine
- General approach
- Proof issues and statistics

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Common Criteria: Evaluation assurance levels (EAL)

Assurance class	Assurance Family	Assurance Components by Evaluation Assurance Level						
		EAL1	EAL2	EAL3	EAL4	EAL5	EAL6	EAL7
Development	ADV_ARC		1	1	1	1	1	1
	ADV_FSP	1	2	3	4	5	5	6
	ADV_IMP				1	1	2	2
	ADV_INT					2	3	3
	ADV_SPM						1	1
	ADV_TDS		1	2	3	4	5	6
Guidance documents	AGD_OPE	1	1	1	1	1	1	1
	AGD_PRE	1	1	1	1	1	1	1
Life-cycle support	ALC_CMC	1	2	3	4	4	5	5
	ALC_CMS	1	2	3	4	5	5	5
	ALC_DEL		1	1	1	1	1	1
	ALC_DVS			1	1	1	2	2
	ALC_FLR							
	ALC_LCD			1	1	1	1	2
	ALC_TAT				1	2	3	3
Security Target evaluation	ASE_CCL	1	1	1	1	1	1	1
	ASE_ECD	1	1	1	1	1	1	1
	ASE_INT	1	1	1	1	1	1	1
	ASE_OBJ	1	2	2	2	2	2	2
	ASE_REQ	1	2	2	2	2	2	2
	ASE_SPD		1	1	1	1	1	1
	ASE_TSS	1	1	1	1	1	1	1
Tests	ATE_COV		1	2	2	2	3	3
	ATE_DPT			1	1	3	3	4
	ATE_FUN		1	1	1	1	2	2
	ATE_IND	1	2	2	2	2	2	3
Vulnerability assessment	AVA_VAN	1	2	2	3	4	5	5

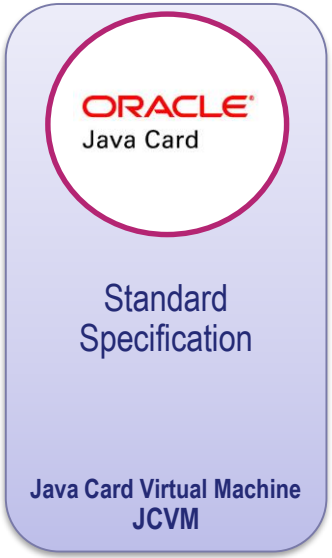
EAL1	Functionally tested
EAL2	Structurally tested
EAL3	Methodically tested and checked
EAL4	Methodically designed, tested and reviewed
EAL5	Semiformally designed and tested
EAL6	**Semiformally verified design and tested**
EAL7	**Formally verified design and tested**

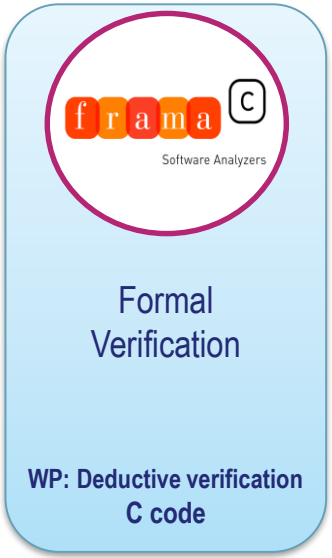
Source:
CCpart3v3.1 - Table 1
(https://www.commoncriteriaportal.org/cc/)

Common Criteria: Certified products (consulted on March 7, 2024)

Certified Products by Assurance Level and Certification Date																
EAL	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**Total**
Basic	0	0	0	0	0	0	0	0	0	0	1	4	38	44	0	87
EAL1	0	0	0	0	0	0	0	0	0	3	4	3	2	0	1	13
EAL1+	0	0	0	0	0	0	0	0	0	0	1	0	2	2	0	5
EAL2	0	0	0	0	0	0	0	1	0	17	15	39	12	12	1	97
EAL2+	0	0	0	0	0	2	1	5	2	28	43	35	30	33	1	180
EAL3	0	0	0	0	0	2	0	0	0	9	9	4	0	2	2	28
EAL3+	0	0	0	0	0	3	1	0	1	4	12	18	29	13	1	82
EAL4	0	0	0	0	0	0	3	0	5	6	5	3	2	3	0	27
EAL4+	1	0	0	0	1	3	7	5	6	44	60	66	73	90	8	364
EAL5	0	0	0	0	0	0	1	0	0	0	2	0	4	2	0	9
EAL5+	0	0	0	0	2	2	4	17	12	41	69	44	39	77	14	321
EAL6	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2
EAL6+	0	0	0	0	0	1	0	0	0	20	20	30	33	37	2	143
EAL7	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	3
EAL7+	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	2
Medium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
None	0	0	0	0	0	0	0	0	0	38	44	77	75	113	13	360
US Standard	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals:	**1**	**0**	**0**	**0**	**3**	**13**	**17**	**28**	**26**	**210**	**286**	**324**	**341**	**431**	**43**	**1723**

Context: three fields of expertise





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Building a future we can all trust

- **C** implementation of the **Standard Specification** of the **JCVM**
- **Formal Security Properties** meet **Security Assurance Requirements**
- **Formal verification** of global formal security properties using **Frama-C/WP**

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JCVM: Standard Specification (1/2)

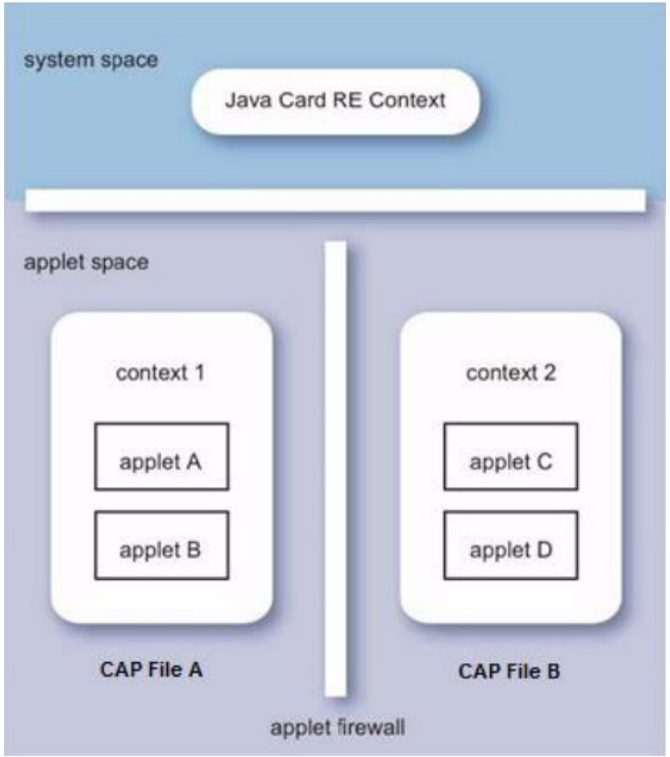
- Execute Java Card applications' bytecode with **basic operations**
- Bytecodes are read iteratively inside the main **dispatch loop**

- 3 main memory areas: Java **stack**, data **heap** and **code** area
- 3 types of **heap** memory: **persistent**, **transient reset/deselect**

- A **unique context** assigned to each Java Card binary (CAP file)
- **Object owner context** is stored inside the object header

JCVM: Standard Specification (2/2)

- The **Firewall guarantees isolation** of heap data between different contexts
- Java Card Runtime Environment (**JCRE**) context is a **privileged context** devoted to system operations
- **Well-defined exceptions:** global arrays, shareable interfaces,…



EAL6-EAL7: Formal verification of Security Properties

Security Aspect

#.Firewall: "*The Firewall shall ensure controlled sharing of class instances, and **isolation of their data and code between packages** (that is, controlled execution contexts) as well as between packages and the JCRE context...*"

[Java Card System – Open Configuration Protection Profile – V3.1]

Security properties (simplified examples)

- **integrity_header**: allocated objects' headers cannot be **modified** during a VM run.
- **integrity_data**: allocated objects' data can be **modified** only by the owner.
- **confidentiality_data**: allocated objects' data can be **read** only by the owner.

Evaluation Assurance Levels

Formal verification of security properties

Frama-C/WP: Formal Deductive Verification

```
/*@
requires P;
assigns  L;
ensures  E;
*/
<type> function(<type> arg1,<type> arg2, …){

    …

    /*@
    loop invariant I;
    loop assigns   L;
    loop variant   m;
    */
    while (c){
     …
    }

     …
}
```

ACSL function contract

ACSL loop contract

Formal Specification Structure

Basic level

STEP1: Write ACSL annotations
(Formal Specification)

STEP2: Frama-C/WP computes proof goals
(Based on Hoare logic)

STEP3: Discharge proof goals with
(QED, Alt-Ergo via Why3, …)

Advanced level features

Ghost code

Predicates, Lemmas

Proof scripts

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Verification of security properties with MetAcsl

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Building a future we can all trust

- **Integrity_data and Confidentiality_data cannot be verified with WP** as global invariants
- We use metaproperties:

name

targets all function(s)

application context:
whenever a location is read

```
meta \prop,\name(meta_persi_objects_confident),\targets(\ALL),\context(\reading),

( \forall integer i; 0 <= i < gNumObjs && !gIsTrans[i] &&
                     ObjHeader[gHeadStart[i] + 0] != JCC ==>
  \separated(\read,PersiData+(gDataStart[i]..gDataEnd[i])) ); */
```

The read location must be separated from the data of any persistent object if the current context is not its owner.

- **MetAcsl** translates metaproperties into **assertions/checks** at each relevant program point.
- If all **assertions/checks** are proved, the metaproperty is proved.
- Thanks to the translation of metaproperties into **checks** that do not overload proof contexts, the metaproperty-based approach scales very well, despite a great number of generated annotations.

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Specification effort

JCVM C code		ACSL Annotations			
		User provided annotations		MetAcsl	RTE
# Functions	# Loc C	# Loc Ghost	# Loc ACSL	# Loc ACSL	# Loc ACSL
381	7,014	162	35,480	396,603	2,290

Large code

A few yet necessary

12,432 before preprocessing macros that gather redundant annotations

Still a considerable effort

Automatically generated from **36** metaproperties only

- **User-provided annotations**: predicates, lemmas, function contracts, loop contracts and other assertions
- **MetAcsl**: automatically generated annotations according to user-defined metaproperties
- **RTE:** automatically generated annotations in order to prevent undefined behaviors

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Some Issues (I), Solutions (S) and Perspectives (P)

Companion ghost model

- **I**: **Automatic proof fails** on low-level code (bit-fields)
- **S:** Linking bits to ghost integer variables brings the **prover back into its comfort zone**
- **P:** **Proof at the abstract level** for some properties can help [as discussed at Dagstuhl]

Proof scripts for complex predicates

- **I:** **Automatic proof fails** to use the right predicates
- **S:** **Guide the first proof steps** by unfolding relevant predicates or instantiating values
- **S&P:** **New proof strategy mechanism** to generate scripts automatically [TACAS'24]

Carefully chosen lemmas

- **I:** **Automatic proof fails** repeatedly in similar cases
- **S:** Lemmas help to **re-use the same reasoning**

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New proof strategy mechanism to generate scripts automatically [TACAS'24]

Instead of creating the proof script interactively in Frama-C/WP

- **With much time** spent for try-and-wait-and-debug attempts

The verification engineer creates a proof strategy

- Written directly **in the source code** as a special annotation
- Including one or **several alternatives** (proof tactics) to try
  - unfolding, rewriting, enumerating, calling a solver,…
- Indicating possible strategies to apply on the **resulting proof goals** (children)
- Possibly attached to **specific proof goals**
- Typically, applied to **help automatic SMT solvers** to prove the goal

The tool automatically tries to apply provided strategies and records a proof script when the proof succeeds

New proof strategy mechanism : examples

Example 1: a lemma unproven in Frama-C/WP with Alt-Ergo

```
lemma vhm_preserved{L1,L2}:
  valid_heap_model{L1} ∧
  mem_model_footprint_intact{L1,L2} ∧
  \at(gNumObjs,L1) == \at(gNumObjs,L2) ∧
  object_headers_intact{L1,L2}
 ⇒ valid_heap_model{L2};
```

A proof strategy that generates a script proving the lemma

```
1   strategy FastAltErgo:  \prover("alt-ergo", 1); // run Alt-Ergo for 1s
2   strategy EagerAltErgo: \prover("alt-ergo",10); // run Alt-Ergo for 10s
3   strategy UnfoldVhmThenProver:                  // Strategy with three steps:
4     FastAltErgo,                                 // 1) fast prover attempt
5     \tactic("Wp.unfold",                         // 2) if unproved, unfold
6       \pattern(P_valid_heap_model((..))),        // predicate valid_heap_model
7       \children(UnfoldVhmThenProver) ),          // and apply itself recursively
8     EagerAltErgo;                                // 3) longer prover attempt
9   proof UnfoldVhmThenProver: vhm_preserved;      // Associate strategy to goal
```


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New proof strategy mechanism : examples

Example 1: a lemma unproven in Frama-C/WP with Alt-Ergo

```
1 lemma dn3:
2   ∀ unsigned char c d;
3  (c & 0x8E) == 2 ∧
4  (c & 0x01) == 1 ∧
5  (d & 0x8F) == 0
6   ⇒ ((c+d) & 0x03) == 0x03;
```

A proof strategy that generates a script proving the lemma

```
1 strategy RangeThenProver:
2   \tactic ("Wp.range",
3     \pattern(is_uint8(e)),
4     \select(e),
5     \param("inf",0),\param("sup",255),
6     \children(RangeThenProver) ),
7   \prover("alt-ergo",2);
8 proof RangeThenProver: dn3;
```


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New proof strategy mechanism : initial experiments

Applied to the proof of the real-life JCVM code at Thales

- 8,000+ lines of C and 30,000+ lines of ACSL
- Complete proof for 85,000 goals using Alt-Ergo with a 250s timeout requires 800+ proof scripts.

With the new extension: significant time savings

- after a manual creation of strategies (~2 days),
- WP automatically produces more than 50% of the required scripts, whose
- Their manual creation would take ~1 person-month.

An even greater number of proof scripts is expected to be generated from strategies

- This will strongly facilitate industrial verification

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Relational properties

- Specification and verification using self-composition
- Verification using a VCGen: formalization and proof in Coq

Relational properties (RPs): how to relate program calls

Monotonicity ?

$$\forall x_1, x_2,\ x_1 < x_2 \Rightarrow f(x_1) < f(x_2)$$

```
/*@ requires 1000 > x;
  @ ensures ?;
  @ assigns \nothing;*/
int f (int x){
   return x + 1;
}
```

How to specify this property ?

How to prove this property ?

How to use this property ?

Specification of relational properties (RPs) in Frama-C

Extension of ACSL:

- New clause relational
- New built-in \callpure

Example with pure function:

```
/*@ requires 1000 > x;
  @ relational \forall int x1,x2; x1 < x2  ==>
  @              \callpure(f,x1) < \callpure(f,x2);
  @ assigns \nothing;*/
int f (int x){
    return x + 1;
}
```

Proposal 1: Proof of relations properties by self-composition [TACAS'17]

- Inspired by Self-composition [Barthe et al (2011)]
- Inline involved function calls
- Express the RP as a standard ACSL assertion

```
void relational_wrapper_1(int x1, int x2){
    int return_1 = x1 + 1;
    int return_2 = x2 + 1;
    /*@ assert x1 < x2 ==> return_1 < return_2; */
    return;
}
```

Express the RP in ACSL

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Proposal 1: Use of relations properties as hypotheses

```
/*@ axiomatic RP_axiom {
  @  logic int f_acsl(int x);
  @
  @ lemma RP_lemma:
  @   \forall int x1, int x2; x1 < x2 ==>
  @         f_acsl(x1) < f_acsl(x2);
}*/

/*@ requires 1000 > x;
  @ assigns \nothing;
  @ ensures \result == f_acsl(x);*/
int f(int x) {
   return x + 1;
}

/*@ relational \forall int x1,x2; x1 < x2  ==>
  @            \callpure(g,x1) < \callpure(g,x2);*/
int g(int x){
    return f(x) + 1;
}
```

Valid if the inserted assertion holds

Assumed: bridge betw. `f` and `f_acsl`

Proved by using the RP for `f`

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A large range of relational properties addressed

Relational Properties (RPs) :

- Invoking at least two function calls
- Invoking possibly dissimilar functions
- Invoking possible nested calls

$$\forall \sigma_1, \ldots, \sigma_n$$

$$P(\sigma_1, \ldots, \sigma_n, [\![f_1]\!]\sigma_1, \ldots, [\![f_n]\!]\sigma_n)$$

A large range of relational properties addressed: some examples

$$\forall x1, x2 \in \mathbb{Z} : \\ x1 < x2 \Rightarrow f(x1) < f(x2)$$

$$\forall\ x; \\ f(x+1) = f(x) * (x+1)$$

$$\forall x,\ f_1(x) \leq f_2(x) \leq f_3(x)$$

$$\forall x, f(f(x)) = f(x)$$

$$\forall\ Msg, Key; \\ Decrypt(Encrypt(Msg, Key), Key) = Msg$$

$$\forall\ t, sub_{t1}, \ldots, sub_{tn}; \\ t = sub_{t1} \cup \ldots \cup sub_{tn} \Rightarrow \\ max(t) = max(max(sub_{t1}), \ldots, max(sub_{tn}))$$

$$\forall x1, x2, y, f(x1 + x2, y) = f(x1, y) + f(x2, y)$$

$$\forall a, b, c,\ \mathrm{Med}(a, b, c) = \mathrm{Med}(a, c, b)$$

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Relational Property Verification: Related Work

- Proof systems (Relational Hoare Logic [Benton, POPL 2004], Relational Separation Logic [Yang. TCS 2007] Cartesian Hoare Logic [Sousa and Dillig. PLDI 2016], Equivalence proofs [Beckert, Ulbrich]...):
  - Separated memory state for each program.
  - Require a dedicated decision system.
  - No modular proofs or relational contracts.
- Code transformations (Self-Composition [Barthe et al. MSCS 2011], Program Products [Barthe, LAMP. 2016], ...):
  - Allow use of verification methods for Hoare Triples.
  - Require renaming and joining the memory state of each tag.
  - No modular proofs or relational contracts.

Proposal 2: Proof of relations properties via a VCGen [iFM'22, ISOLA'22]

- Relational property verification based on a VCGen (verification condition generator)
- Enabling modular verification of relational properties
- Fully formalized and proved sound in the Coq proof assistant for a while language with procedures and aliasing.

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Relational property, formally

A Relational Property is a property about n programs $c_1, ..., c_n$: if each program c_i starts in σ_i and ends in $\sigma'_i = [\![c_i]\!]_\psi \sigma_i$ such that $(\sigma_1, ..., \sigma_n)$ satisfies $\widehat{P}$, then $(\sigma'_1, ..., \sigma'_n)$ satisfies $\widehat{Q}$.

$$\forall \sigma_1, \ldots, \sigma_n, \widehat{P}(\sigma_1, \ldots, \sigma_n) \Rightarrow \widehat{Q}(\sigma_1, \ldots, \sigma_n, [\![c_1]\!]_\psi \sigma_1, \ldots, [\![c_n]\!]_\psi \sigma_n)$$

We use following notation for Relational Properties:

$$\psi : \{\widehat{P}\}(c_k)^n\{\widehat{Q}\}.$$

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Example of relational property

We want to prove that both programs below are equivalent:

$$\{\ x_2\langle 1\rangle = x_2\langle 2\rangle\ \}\quad \begin{array}{l} x_1 := 1; \\ x_3 := 0; \\ \textbf{call}(y_{\mathrm{sum}}) \end{array} \quad \langle 1\rangle \sim \quad \begin{array}{l} x_1 := 0; \\ x_3 := 0; \\ \textbf{call}(y_{\mathrm{sum}}) \end{array} \quad \langle 2\rangle\ \{\ x_3\langle 1\rangle = x_3\langle 2\rangle\ \}$$

With procedure environment $\{y_{\mathrm{sum}} \to \mathrm{body}(y_{\mathrm{sum}})\}$ where:

$$\mathrm{body}(y_{\mathrm{sum}}) = \begin{array}{l} \textbf{if } x_1 < x_2 \textbf{ then } \{ \\ \quad x_3 := x_3 + x_1; \\ \quad x_1 := x_1 + 1; \\ \quad \textbf{call}(y_{\mathrm{sum}}) \\ \} \textbf{ else } \{ \textbf{ skip } \} \end{array}$$

Verification Condition Generator (VCGen): main principle

Construction of first-order formulas whose validity implies the validity of the Hoare Triple.

- Naive generation: *if* statements make the size of the formulas grow exponantially.
- Optimized generation: the formulas size is lineare in the size of the initial program.

Verification Condition Generator (VCGen): main principle

- $\mathcal{T}_c$ generates the main verification condition: the postcondition holds in the final state, assuming auxiliary annotations hold;
- $\mathcal{T}_a$ generates auxiliary verification conditions stemming from assertions, loop invariants, and preconditions of called procedures;
- $\mathcal{T}_f$ generates verification conditions for the auxiliary procedures.

Theorem: VCGen is sound

If

$$\forall \sigma \in \Sigma, P(\sigma) \Rightarrow \mathcal{T}_c[\![c]\!](\sigma, \phi, Q),$$

$$\forall \sigma \in \Sigma, P(\sigma) \Rightarrow \mathcal{T}_a[\![c]\!](\sigma, \phi),$$

$$\mathcal{T}_f(\phi, \psi),$$

then we have $\psi : \{P\}c\{Q\}$.

Verification of relational properties with VCGen

What do we want

For each command in a relational property, we separately generate the associated logical formulas.

Proposal

Using extensions of $\mathcal{T}_c$, $\mathcal{T}_a$ and $\mathcal{T}_f$, we translate the relational verification problem directly into first-order formulas.

Relational Verification Condition Generator (VCGen)

Construction of first-order formulas whose validity implies the validity of the Relational Property.

- $\mathcal{T}_{cr}$ generates the main verification condition (using $\mathcal{T}_c$): the relational postcondition holds in the final state, assuming auxiliary annotations hold;
- $\mathcal{T}_{ar}$ generates auxiliary verification conditions (using $\mathcal{T}_a$) stemming from assertions, loop invariants, and preconditions of called procedures;
- $\mathcal{T}_{pr}$ translates relational contracts into first order formulas;
- $\mathcal{L}$ lifts relational contract environment into a standard contract environment;
- $\mathcal{T}_{fr}$ generates verification conditions for the procedures: procedure bodies respect their relationals contracts.

Relational Verification Condition Generator (VCGen) is sound

Theorem: Relational VCGen is sound

If

$$\forall (\sigma_k)^n, (\sigma'_k)^n, \psi', \quad \widehat{P}((\sigma_k)^n) \wedge \mathcal{T}_{pr}(\widehat{\phi}, \psi') \Rightarrow$$
$$\mathcal{T}_{cr}((c_k)^n, (\sigma_k)^n, (\sigma'_k)^n, \mathcal{L}(\widehat{\phi}, \psi'))\ \lambda p.\, p \Rightarrow \widehat{Q}((\sigma_k)^n, (\sigma'_k)^n),$$

and

$$\forall (\sigma_k)^n, \psi', \quad \widehat{P}((\sigma_k)^n) \wedge \mathcal{T}_{pr}(\widehat{\phi}, \psi') \Rightarrow$$
$$\mathcal{T}_{ar}((c_k)^n, (\sigma_k)^n, \mathcal{L}(\widehat{\phi}, \psi')),$$

and

$$\mathcal{T}_{fr}(\widehat{\phi}, \psi),$$

then we have $\psi : \{\widehat{P}\}(c_k)^n\{\widehat{Q}\}$.

Conclusion

Successful industrial application of deductive verification

- World-first proof of real-life JavaCard VM code
- EAL7 certificate issued by ANSSI, the French certification body
- Careful combination of: ghost code, lemmas, proof scripts, …
- High level of automation (99% of goals proved automatically)
- MetAcsl is crucial for specification of security properties
- Proof integrated into the Continuous Integration process
- Efficient tool support from Frama-C developers was essential

Promising approach for relational property verification based on a VCGen

- Modular verification of Relational Properties
- Separated memory state for each program
- Proven sound in the Coq proof assistant
- Relies on optimized verification condition generation

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Ongoing and future work directions

Custom and more flexible proof strategies to save manual script creation effort

- New extension of Frama-C/WP for proof strategies to be presented at TACAS 2024
- About 50% of necessary proof scripts are generated automatically!

Reasoning about metaproperties and other annotations can be helpful

- Preliminary ideas proposed in Virgile Robles' PhD thesis
- Externalizing verification of metaproperties at the callsite for two functions reduced proof time by 1 hour!!

Scaling to large programs having parts with and without low-level operations, or where some of the maintained properties are irrelevant

- Collaborative memory models
- More abstract levels of reasoning

Developing industry-ready sound tools for verification of relational properties

Participating in collaborative projects to apply innovative verification techniques to Thales products

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