Formal verification of a JavaCard Virtual Machine with Frama-C

Initially presented at FM 2021

Nikolai KOSMATOV
Joint work with Adel DJOUDI, Martin HANA

CEA List, Palaiseau, December 16, 2021

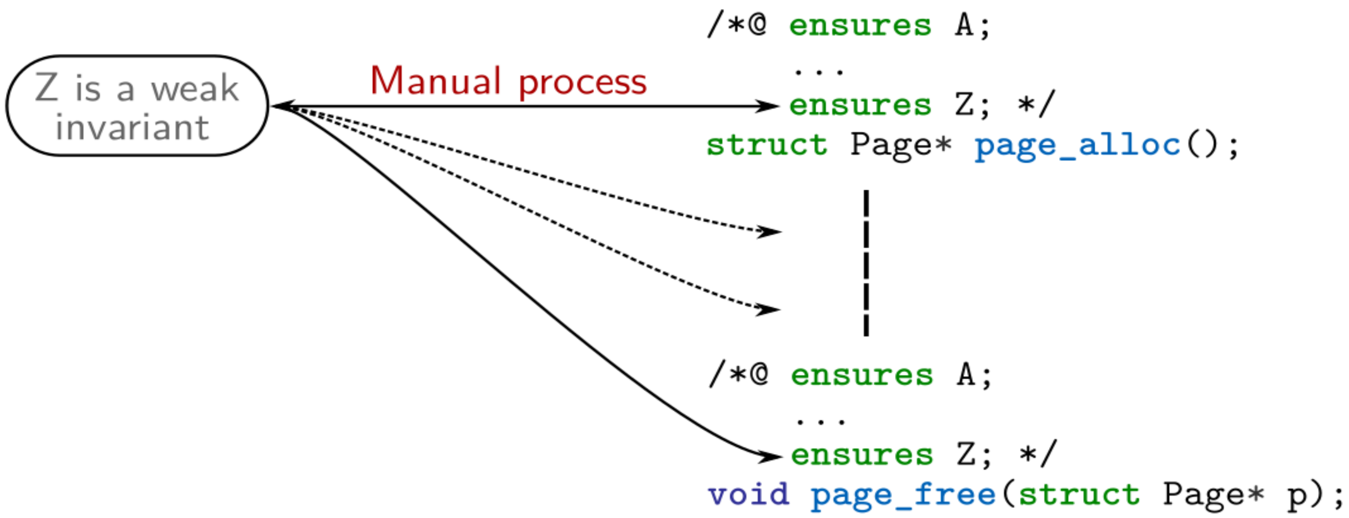
Part I*. Global Property Verification with MetAcsl

- Motivation: Specification and verification of global properties
- Solution: High-Level ACSL Requirements (HILARE)
- Examples of Proof with MetAcsl and WP

*Some slides prepared by Virgile Robles

Motivation: Global (High-Level) Properties

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.

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: Meta-properties, 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;
```

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;
```

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));
```

Example: Strong Invariant

```
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; */ ;
}
```

test2.c

```
int A, B, C;
/*@
  meta \prop, \name(A_B_eq_strong),
    \targets(\ALL), \context(\strong_invariant),
    A == B;  // FAILS
*/
/*@
  requires A==B;
  assigns A,B;
  ensures C>=0 && A==C && B==C ||
    C<0 && A==\old(A) && B==\old(B); */
void foo(){
  if ( C >= 0 ){
    A = C;
    B = C;
  }
}

```

Example: Weak Invariant

```
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;
}
```

test3.c

```
int A, B, C;
/*@
  meta \prop, \name(A_B_eq_weak),
    \targets(\ALL), \context(\weak_invariant),
    A == B;
*/
/*@
  requires A==B;
  assigns A,B;
  ensures C>=0 && A==C && B==C ||
    C<0 && A==\old(A) && B==\old(B); */
void foo(){
  if ( C >= 0 ){
    A = C;
    B = C;
  }
}

```

Example: Reading Context

```
/*@ 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;
}
```

test4.c

```
int A, B, C;
/*@
  meta \prop, \name(A_not_read),
    \targets(\ALL), \context(\reading),
    \separated(\read, &A);
*/
/*@
  requires A==B;
  assigns A,B;
  ensures C>=0 && A==C && B==C ||
    C<0 && A==\old(A) && B==\old(B); */
void foo(){
  if ( C >= 0 ){
    A = C;
    B = C;
  }
}

```

Example: Writing Context

```
/*@ meta "A_unchanged_unless";
 */
/*@ requires 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) {
    /*@ 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;
}
```

test5.c

```
int A, B, C;
/*@
  meta \prop, \name(A_unchanged_unless),
      \targets(\ALL), \context(\writing),
      C < 0 ==> \separated(\written, &A);
*/
/*@
  requires A==B;
  assigns A,B;
  ensures C>=0 && A==C && B==C ||
    C<0 && A==\old(A) && B==\old(B); */
void foo(){
  if ( C >= 0 ){
    A = C;
    B = C;
  }
}
```

Part II: Proof of JavaCard Virtual Machine

- Introduction
- General approach
- Proof issues and solutions
- Results and conclusion

Context: three fields of expertise

ORACLE Java Card

Standard Specification

Java Card Virtual Machine JCVM

COMMON CRITERIA

Security Assurance Requirements

Evaluation Assurance Level EAL6

frama C Software Analyzers

Formal Verification

WP: Deductive verification C code

THALES 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**

OPEN

THALES

JCVM: Standard Specification (1/2)

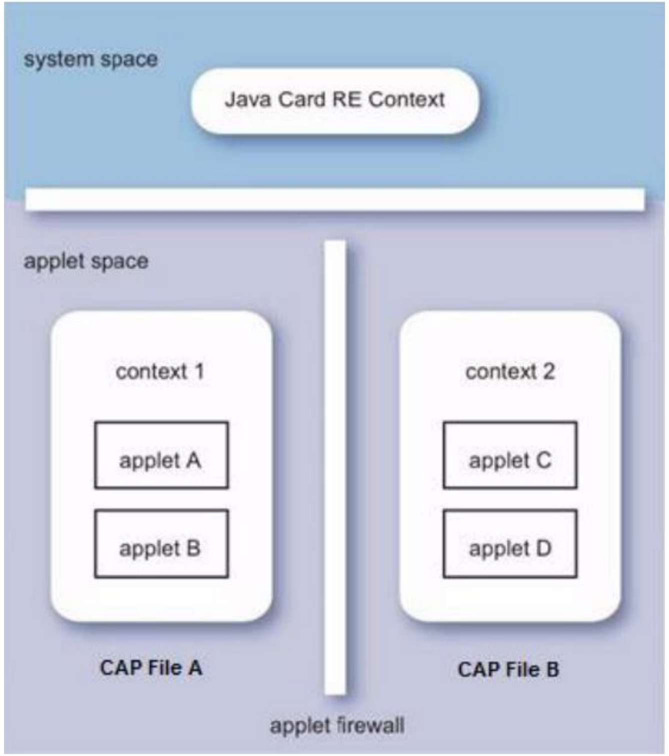
- Execute Java Card applications' bytecode with **basic operations**
- Bytecodes are read iteratively inside the main **dispatch loop**

- 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,…



OPEN

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/)

OPEN

THALES

EAL6: Formal verification of Security Properties

COMMON CRITERIA

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

EAL1	EAL2	EAL3	EAL4	EAL5	EAL6	EAL7

Formal verification

Formal verification of security properties

THALES

Overview

- Introduction
- General approach
- Proof issues and solutions
- Results and conclusion

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

OPEN

FRAMA-C/RTE,MetAcsl : two other necessary plugins

Automatically generated ACSL assertions inserted at appropriate program points

- **RTE**: proves absence of undefined behaviors (no user input)
- **MetAcsl**: proves global properties (user needs only to specify metapropeties)

name

target function(s)

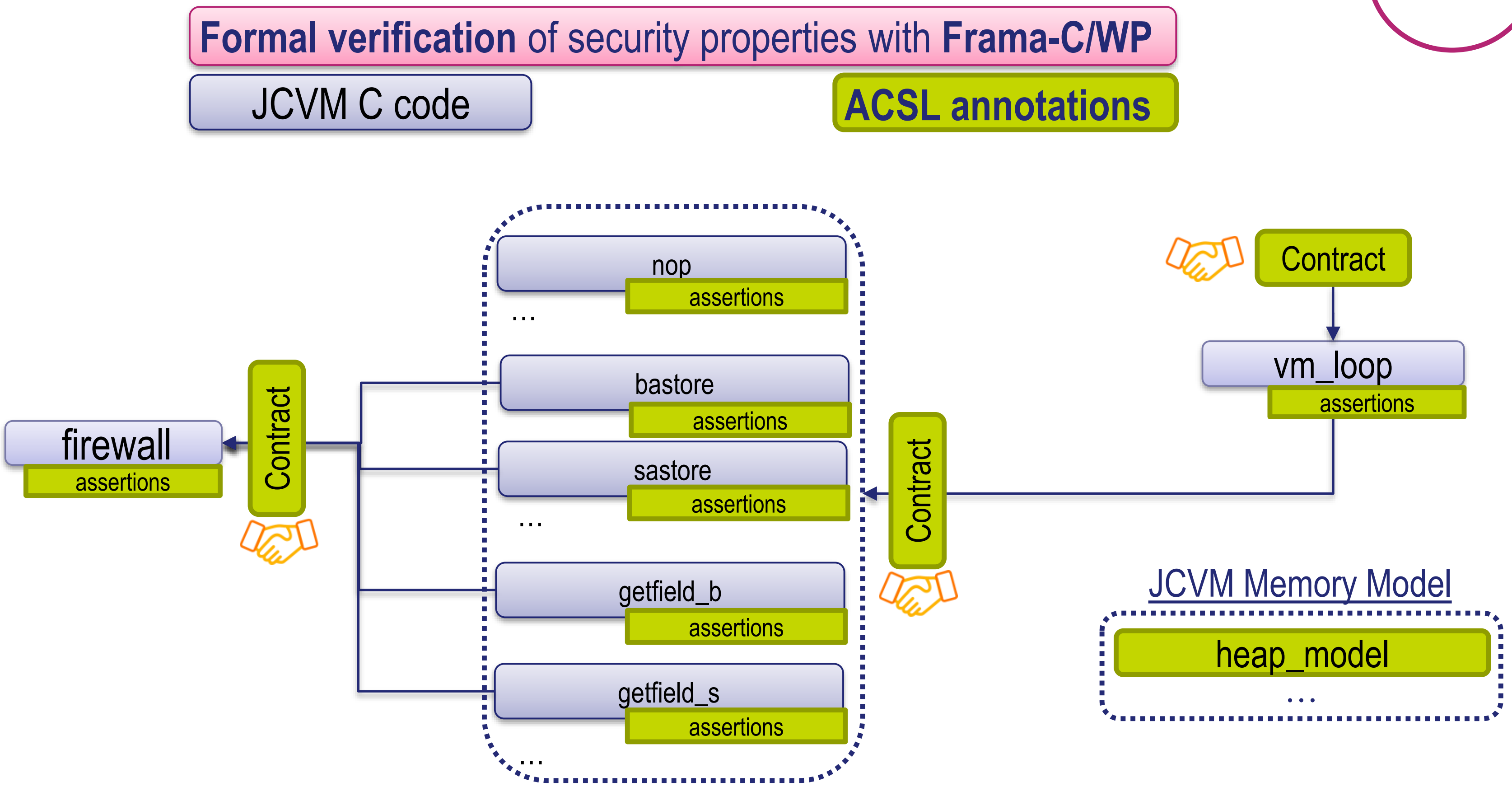
application context:
e.g. when any location is read

property

```
/*@ meta \prop, \name(m), \targets(F), \context(\reading), (\separated(\read, &Data[0..10])); */

// array Data can not be read in the set of target functions F

int Data[11]; // array containing sensitive data (not to be disclosed!)

…
```

OPEN

JCVM Call Graph (toy example)



Memory segments

- Object headers: `unsigned char ObjHeader[SEGM_SIZE];`
- Persistent/Transient object data:
  `unsigned char PersiData[SEGM_SIZE], TransData[SEGM_SIZE];`

ACSL predicates for memory model constraints

- **Ex. predicate** valid_heap_model
  - Number of allocated objects is within allowed bounds
  - Headers are in corresponding segment bounds and do not overlap
  - Data are in corresponding segment bounds and do not overlap

ACSL predicates for security properties

- **Ex. predicate** object_headers_intact{L1, L2}
  - Object headers of allocated objects do not change between labels L1 and L2 (**integrity_header**)

Bastore : function contract

```
99  /*@
100 requires vhm: valid_heap_model;
101 requires …;
102 assigns  …;
103 ensures  …;
104 ensures  vhm: valid_heap_model;
105 ensures  oh: object_headers_intact{Pre, Post};
106 */
107 void bastore(u4 ObjRef, u4 DestOff, u1 Val){          // u1/u4: unsigned char/int
108   if( ! firewall(ObjRef,DestOff) )                    // Check access and
109    return;                                            // exit if forbidden
110   if( GET_FLAG(ObjHeader+ObjRef) & 0x08 )             // If transient bit set,
111    TransData[GET_OFF(ObjHeader+ObjRef) + DestOff] = Val; // write to transient body
112   else                                                // Otherwise
113    PersiData[GET_OFF(ObjHeader+ObjRef) + DestOff] = Val; // write to persistent body
114   updateJPC();
115 }
```

toy example

- **Bastore:** write value **Val** into a given array at a given offset
- **valid_heap_model** is maintained both as **pre-condition** and **post-condition**
- Line 105 ensures security property **integrity_header**
- **Firewall** is called to check the access

Main dispatch loop

```
void vm_loop(){
  /*@
  loop invariant vhm: valid_heap_model;
  loop invariant …
  loop invariant oh: object_headers_intact{LoopEntry, Here};
  loop assigns …
  …
  …
  …
  */
  while(1){
…
    // calls opcode functions (bastore, …)
…
  }
}
```

valid_heap_model is maintained as a loop invariant

Security Property is maintained as a loop invariant

toy example

OPEN

Verification of security properties with MetAcsl

- Integrity_data and Confidentiality_data **cannot be specified (easily) with WP** as global invariants

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.

Overview

- Introduction
- General approach
- Proof issues and solutions
- Results and conclusion

THALES

Some Issues (I) and Solutions (S)

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**

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

Carefully chosen lemmas

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

OPEN

THALES

Low-level operations (examples)

Low-level bit-field operations

- Transient bit obtained from flag byte with mask 0x08
- Companion ghost encoding to help the prover: `unsigned char gIsTrans [MAX_OBJS];`

```
predicate valid_heap_model =
…
    (\forall integer i; 0 <= i < gNumObjs ==>
      ( gIsTrans[i] <==> (GET_FLAG(ObjHeader+gHeadStart[i]) & 0x08) ) ) &&
…
```

Frama-C/WP “Typed” memory model does not allow pointer casts

- We rewrite some pointer casts

```
typedef unsigned char u1; typedef unsigned short u2;
…
#define GET_OFF(addr) ( (u2)((*((u1*)addr + 4))*256 + *((u1*)addr + 5)) )
// instead of
// #define GET_OFF(addr)((u2)(*(u2*)(addr + 4)))
```

Lemmas to deduce some complex predicates (1/2)

Complex preservation properties

- Lemmas help automatic provers to prove complex preservation properties

```
/@
lemma vhm_preserved{L1,L2}:
  mem_model_footprint_intact{L1,L2} &&
  object_headers_intact{L1,L2} &&
  valid_heap_model{L1} &&
  \at(gNumObjs,L1) == \at(gNumObjs,L2) ==>
     valid_heap_model{L2};
*/
```

Lemmas to deduce some complex predicates (2/2)


```
/*@ // === A security property: object headers remain intact ===
predicate object_headers_intact{L1, L2} =
  \forall integer i, off; 0 <= i < \at(gNumObjs,L1) &&
  \at(gHeadStart[i],L1) <= off < \at(gHeadStart[i],L1) + 8 ==>
  \at(ObjHeader[off],L1) == \at(ObjHeader[off],L2);

// === Memory footprint predicate and lemma example ===
predicate mem_model_footprint_intact{L1,L2} =
  \at(gNumObjs,L1) <= \at(gNumObjs,L2) &&
  ( \forall integer i; 0 <= i < \at(gNumObjs,L1) ==>
  \at(gIsTrans[i],L1) == \at(gIsTrans[i],L2) &&
  \at(gHeadStart[i],L1) ==\at(gHeadStart[i],L2) &&
  \at(gDataStart[i],L1) ==\at(gDataStart[i],L2) &&
  \at(gDataEnd[i],L1) ==\at(gDataEnd[i],L2) );

lemma vhm_preserved{L1,L2}: mem_model_footprint_intact{L1,L2} &&
  object_headers_intact{L1,L2} && valid_heap_model{L1} &&
  \at(gNumObjs,L1) == \at(gNumObjs,L2) ==> valid_heap_model{L2}; */
```

toy example

- Object headers do not change between labels L1 and L2
- Relevant memory footprint does not change between labels L1 and L2 for objects that existed at label L1.
- Helps automatic provers to prove complex preservation properties.

OPEN

THALES

Overview

- Introduction
- General approach
- Proof issues and solutions
- Results and conclusion

THALES

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

Proof results for 4 increasing code subsets

The proof scales well with an increasing number of goals

		User-provided ACSL	MetAcsl	RTE	Total	
Code subset	Prover	#Goals	#Goals	#Goals	#Goals	Time
Bastore	Qed	1,019	3,304	106	4,429 (**77.92%**)	0h47m45s
	Script	78	131	1	210 (3.69%)	0h11m12s
	SMT	305	590	148	1,043 (18.35%)	0h17m23s
	All	1,402 (24.67%)	4,025 (**70.81%**)	255 (4.48%)	**5,684**	**0h49m37s**
Sample 1	Qed	1,491	5,037	120	6,648 (**79.76%**)	1h00m49s
	Script	111	149	7	267 (3.20%)	0h13m41s
	SMT	437	784	199	1,420 (17.03%)	0h28m24s
	All	2,039 (24.46%)	5,970 (**71.63%**)	326 (3.91%)	**8,335**	**0h59m59s**
Sample 2	Qed	2,413	6,884	126	9,423 (**79.43%**)	1h04m33s
	Script	144	257	20	421 (3.55%)	0h18m15s
	SMT	682	1,088	249	2,019 (17.01%)	0h37m01s
	All	3,239 (27.30%)	8,229 (**69.36%**)	395 (3.33%)	**11,863**	**1h09m47s**
All	Qed	18,925	22,361	168	41,454 (**79.42%**)	2h58m15s
	Script	330	212	30	572 (1.1%)	0h44m48s
	SMT	4,683	4,588	902	10,173 (19.49 %)	2h36m18s
	All	23,938 (**45.85%**)	27,435 (**52.55%**)	1,117 (2.13%)	**52,198**	**3h28m07s**

99% of proof goals discharged automatically (QED + Alt-Ergo)
Manual effort is still important (a few days to update scripts !)

OPEN

THALES

Conclusion

Successful industrial application of deductive verification

- EAL 6 certificate issued by ANSSI after evaluation by CEA Leti
- 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
- Efficient tool support from Frama-C developers was essential

Future work directions

- Introduce proof into a continuous integration process
- Better support for custom proof strategies to save manual script effort
- Accelerate QED simplification for complex functions with lots of branches
- 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
- Better parallelization of the proof with WP (in particular, QED)

THALES

References

- Adel Djoudi, Martin Hana and Nikolai Kosmatov.
"Formal verification of a JavaCard virtual machine with Frama-C".
In *Proc. of the 24rd International Symposium on Formal Methods (**FM 2021**),*
Online, November 2021, pages 427-444. LNCS, vol. 13047. Springer.
- Virgile Robles, Nikolai Kosmatov, Virgile Prevosto, Louis Rilling, and Pascale Le Gall.
"MetAcsl: Specification and Verification of High-Level Properties."
In Proc. of the 25th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (**TACAS 2019**), pages 358-364, LNCS, vol. 11427. Springer.
- Virgile Robles, Nikolai Kosmatov, Virgile Prevosto, Louis Rilling, and Pascale Le Gall.
"Tame your annotations with MetAcsl: Specifying, Testing and Proving High-Level Properties".
In Proc. of the 13th International Conference on Tests & Proofs (**TAP 2019**), pages 167-185. LNCS, vol. 11823. Springer.
- Virgile Robles, Nikolai Kosmatov, Virgile Prevosto, Louis Rilling, and Pascale Le Gall.
"Methodology for Specification and Verifiation of High-Level Properties with MetAcsl".
In Proc. of the 9th IEEE/ACM International Conference on Formal Methods in Software Engineering (**FormaliSE 2021**), IEEE.