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Formal verification of a JavaCard Virtual Machine with Frama-C

Initially presented at FM 2021

Nikolai KOSMATOV
Joint work with Adel DJOUDI, Martin HANA

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Overview

Why do we certify products?

COMMON CRITERIA

For compliance

- Certificate is required by national or European regulations (e.g for e-sign)
- Certificate is required by customers

Value standardized security for customers

- To give confidence in our products
- Products are evaluated by competent and independent licensed laboratory
- Security certificates are issued by national Certification Bodies

A business strategy

- For communication and marketing
- To raise the bar for competitors on some markets

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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**

JCVM: Standard Specification (1/2)

ORACLE Java Card

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

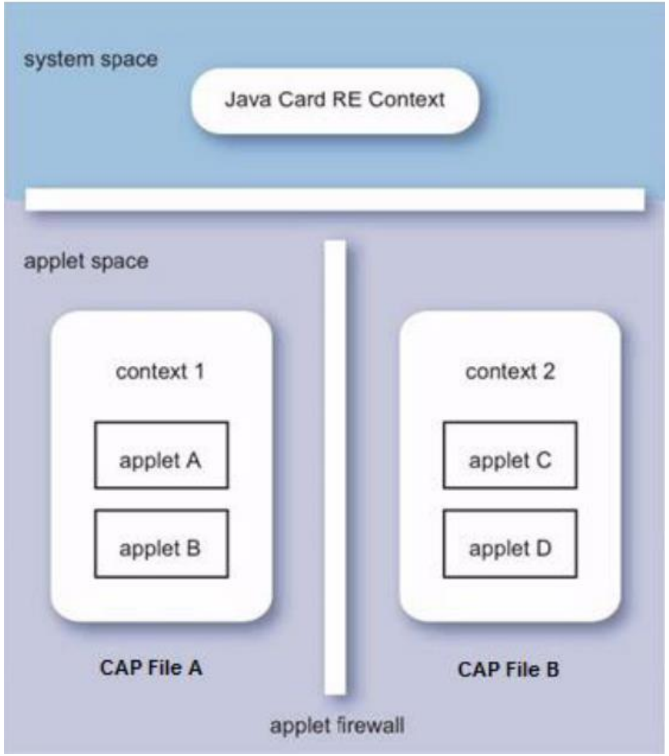
- 3 main memory areas: Java **stack**, data **heap** and **code** area
- 3 types of **heap** memory: **persistent**, **transient reset/deselect**

- 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)

ORACLE
Java Card

- 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,…



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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/)

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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

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Overview

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

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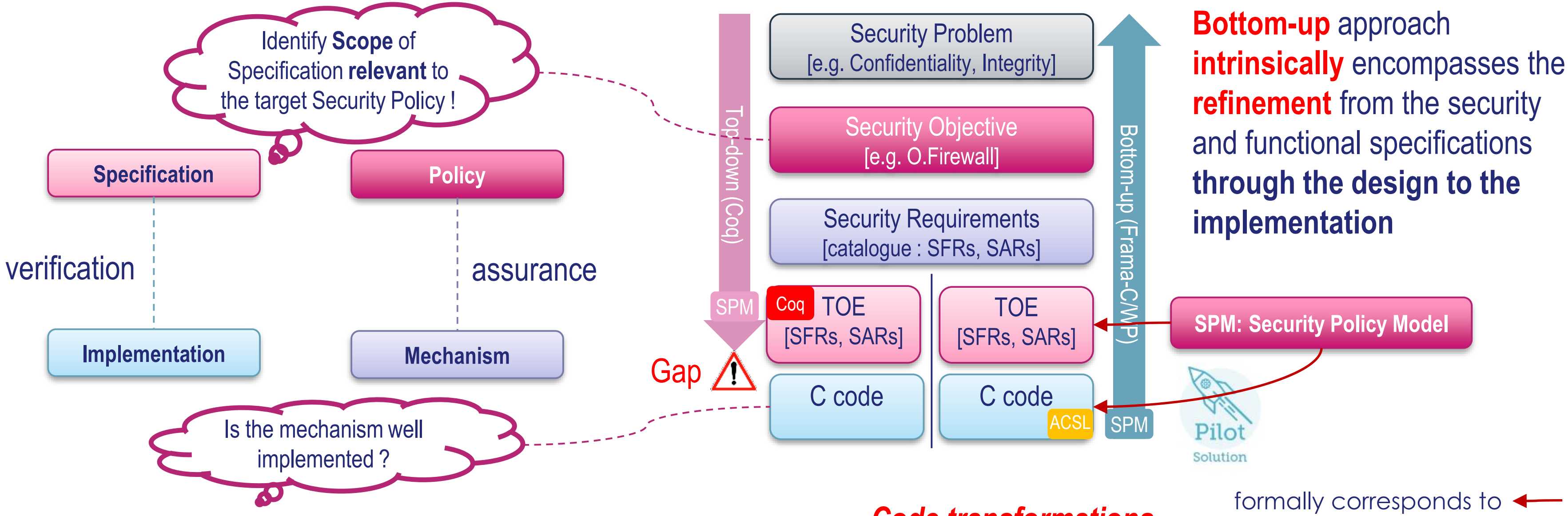
Certification Methodology Overview: Novel Bottom-up Approach



Bottom-up approach **intrinsically** encompasses the **refinement** from the security and functional specifications **through the design to the implementation**

***Code transformations** are however needed due to proof tool limitations.*

__Further details in__ **: Djoudi et al, ERTS 2022.**

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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

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

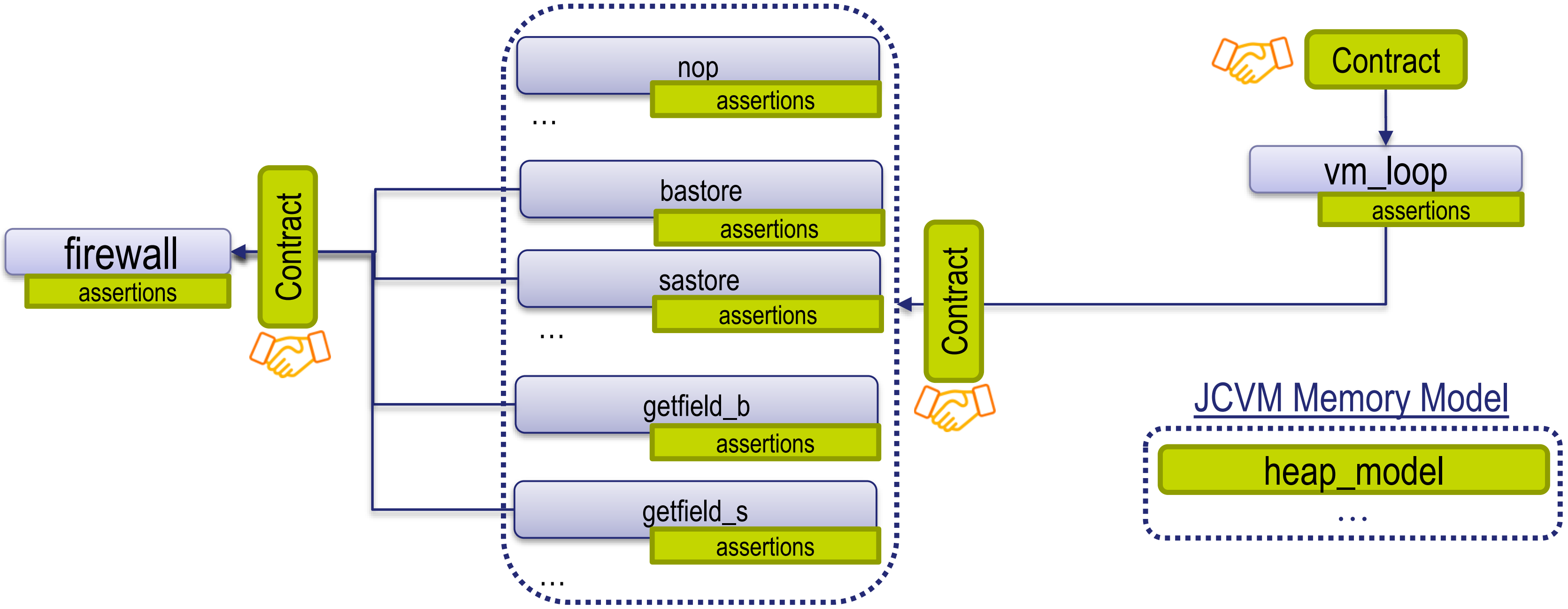
```
/*@ meta \prop, \name(m), \targets(F), \context(\reading), (\separated(\read, &Data[0..10])); */
// array Data can not be read in the set of target functions F
int Data[11]; // array containing sensitive data (not to be disclosed!)
...
```

JCVM Call Graph (toy example)

Formal verification of security properties with **Frama-C/WP**

JCVM C code

ACSL annotations



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

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.

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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**

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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)))
```

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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.

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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

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 !)

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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)

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