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Retrospective on Formal Verification of a JavaCard Virtual Machine with Frama-C

Adel Djoudi, Nikolai KOSMATOV

Joint work with Martin HANA

Journées GDR Sécurité
Rennes, June 10, 2024

Outline

- Frama-C verification platform
- Specification and verification of security properties with MetAcsl
- Common Criteria Certification
- Experience of Verification of JavaCard Virtual Mathine
- Ongoing and Future Work

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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, …
- **RTE** plugin used to generate annotations preventing runtime errors or undefined behavior
  - invalid memory accesses, arithmetic overflows, division by zero…

Software Analyzers

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

High-level (security) properties are hard to specify and verify in Frama-C

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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Security Properties as Metaproperties

Writing context: for integrity

- The given predicate must hold whenever the memory is modified.
- The predicate uses a predefined variable `\written` that refers to the written memory location.
- Typically, we specify that some variable `Var` is not written by `\separated(&Var,\written)`

Reading context: for confidentiality

- The given predicate must hold whenever the memory is read.
- The predicate uses a predefined variable `\read` that refers to the read memory location.
- Typically, we specify that some variable `Var` is not read by `\separated(&Var,\read)`

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Examples of Metaproperties

```
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: 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
{
  (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

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

MetAcsl

Initial C code:

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;
  }
```

MetAcsl instantiates a metaproperty in all relevant locations

Common Criteria Certification for Integrated Circuits and Smart cards

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Building a future we can all trust

Common Criteria

EAL7
EAL6
EAL5
EAL4
EAL3
EAL2
EAL1

Formal verification required for EAL6/EAL7

Meet High-security requirements of customers.

Chips in ID documents are tiny computers with embedded Operating System and applications.

We apply **deductive verification** with **Frama-C/WP** on a **C implementation** of a **Java Card Virtual Machine.**

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Constraints of application of Formal Methods in Industry

Formal Model Expressivity

Ensure expressivity of specification language

Formal Model Representativity

Ensure traceability of verified properties

Verification Efficiency

Ensure scalability on large code

Verification tool features

Ensure automation whenever possible

Common Criteria : security policy and security mechanism

Firewall Security Aspect

"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 problem**

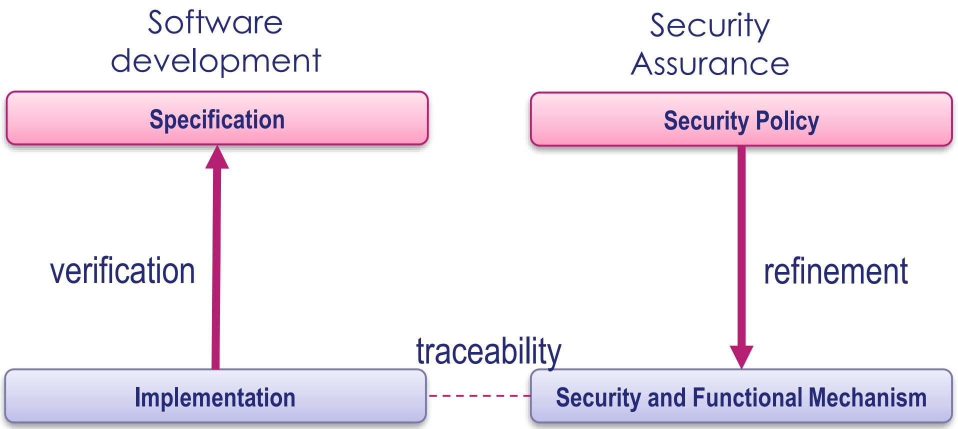
- Threats to Confidentiality and Integrity

> **Security Objective**

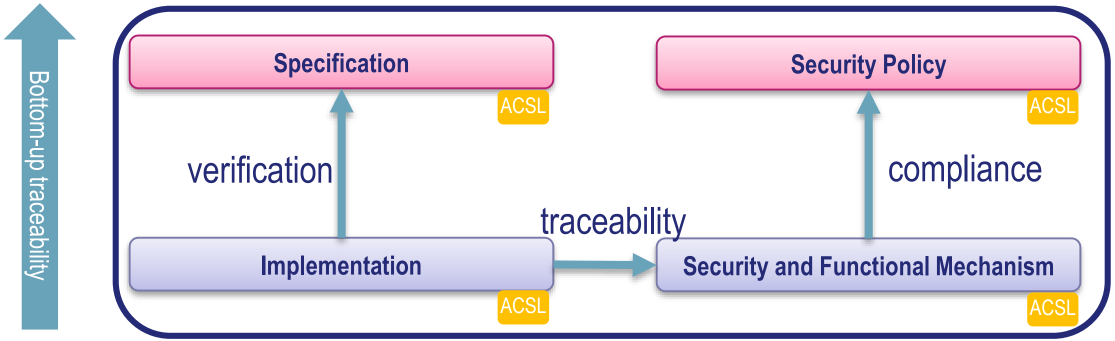
- Ensure isolation of data according to their owners

> **Security Requirements**

- Catalogue of security mechanisms related to the Firewall



Novel Bottom-up approach : intrinsic refinement



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.*

Formal interpretation of CC requirements with ACSL

(ERTS 2022) A Bottom-Up Formal Verification Approach for Common Criteria Certification: Application to JavaCard Virtual Machine (jointly with ANSSI and CEA-Leti, **best paper award**)

JCVM Memory Model and Formal SPM

Memory segments (ghost/abstract representation)

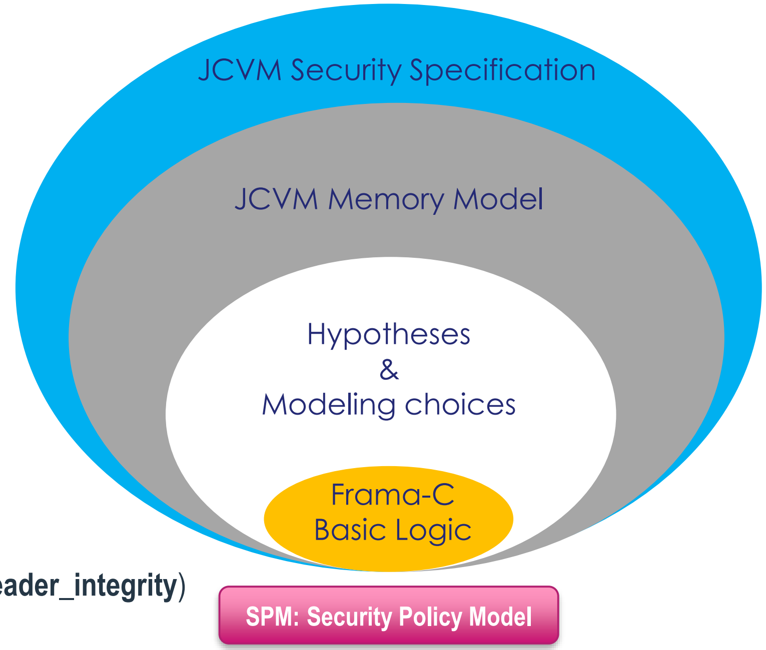
- **E.g.** Object headers: `unsigned char ObjHeader[SEGM_SIZE];`
- **E.g.** Persistent/Transient object data: `unsigned char PersiData[SEGM_SIZE], TransData[SEGM_SIZE];`

ACSL predicates for memory model constraints

- **E.g. 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
  - The ghost/abstract representation complies with real implementation

ACSL predicates for security properties

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



Bastore : function contract example

```
…    /*@ admit requires bcv: valid_ref_or_null;              // Admitted hypothesis without proof
103      requires vhm: valid_heap_model;
104      ensures  vhm: valid_heap_model;
105      ensures  oh: object_headers_intact{Pre, Post}; */
106 void aastore(u4 ObjRef, u4 DestOff, u1 Ref){             // u1/u4: unsigned char/int
107   if( ! firewall(ObjRef,DestOff) )                       // Check access and
108    return;                                               // exit if forbidden
109   if( GET_FLAG(ObjHeader+ObjRef) & 0x08 )                // If transient bit set,
110    TransData[GET_OFF(ObjHeader+ObjRef) + DestOff] = Ref; // write to transient body
111   else                                                   // Otherwise
112    PersiData[GET_OFF(ObjHeader+ObjRef) + DestOff] = Ref; // write to persistent body
113   updateJPC();
114 }
```

toy example

- **aastore:** write value **Ref** 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

Properties propagated up to the main dispatch loop and maintained as global loop invariants.

Further details in : Djoudi, A., Hána, M., Kosmatov, N., *Formal Verification of a JavaCard Virtual Machine with Frama-C*. FM 2021.

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Tool challenge: deductive verification of global security properties

Expressivity challenge

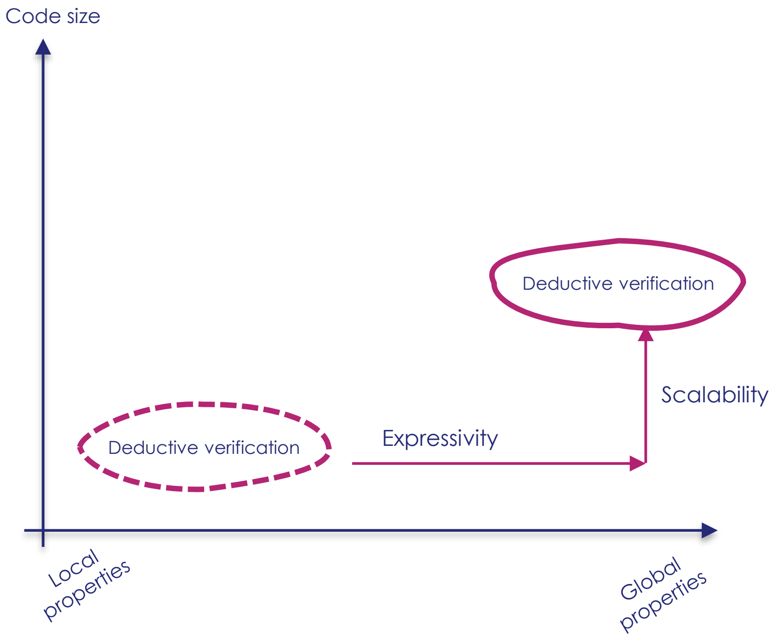
- Initial uncertainty about ability to specify high-level global security properties (confidentiality & integrity) with **ACSL**

Local properties

- **Frama-C/RTE** ensures that code is free of undefined behaviors

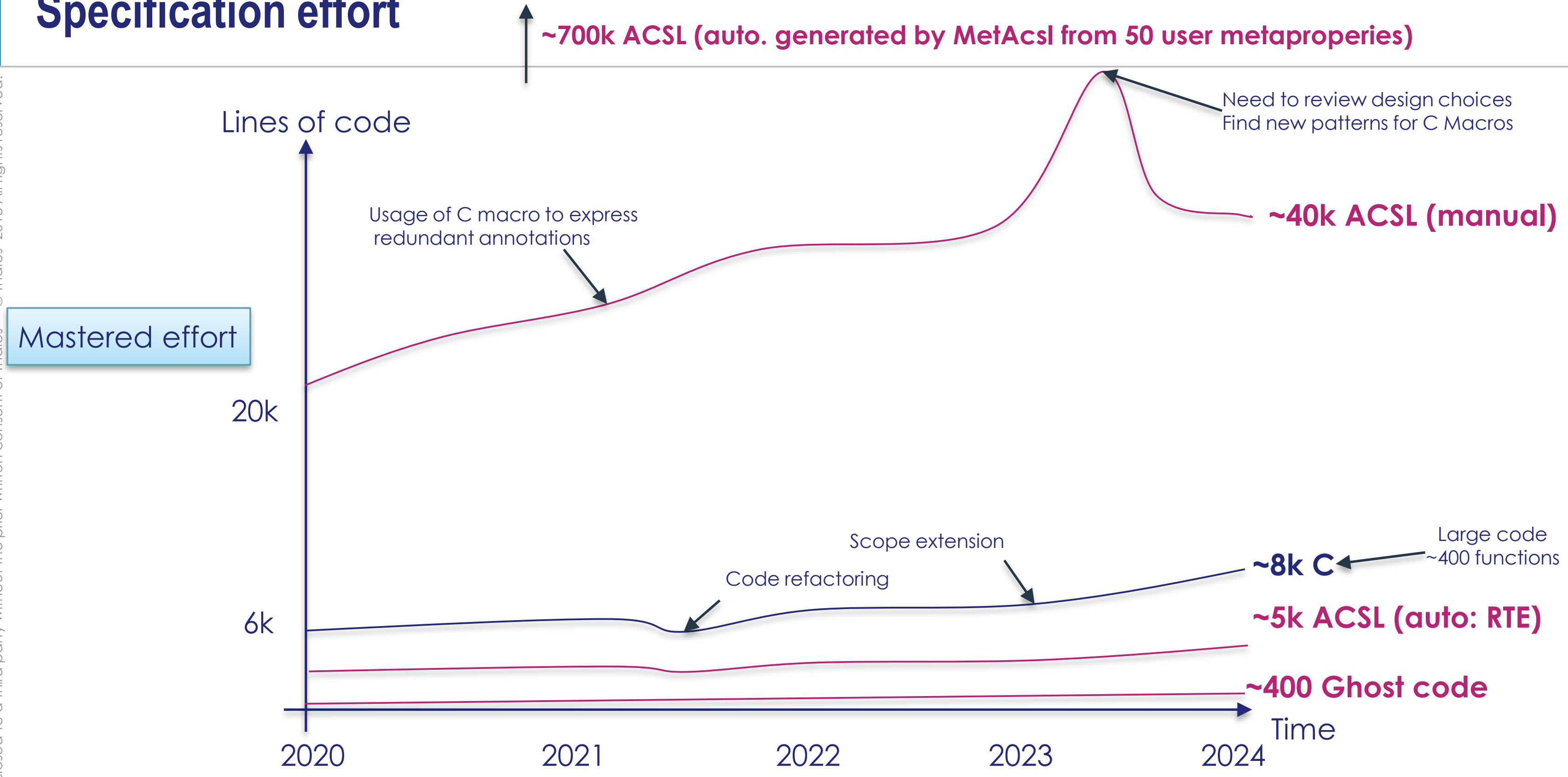
Global properties

- **Frama-C/WP** ensures weak global invariants (maintained at function calls and returns, at loop invariants and at some asserts)
- **FRAMA-C/MetAcsl** ensures strong global invariants (maintained at every sequence point in the program)



(FM 2021) Formal Verification of a JavaCard Virtual Machine with Frama-C

Specification effort



(2024) Proof of Security Properties: Application to JavaCard Virtual Machine (chapter in Springer book series CSFAL: Guide to Software Verification with Frama-C)

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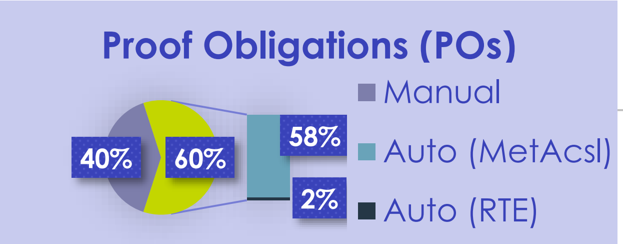
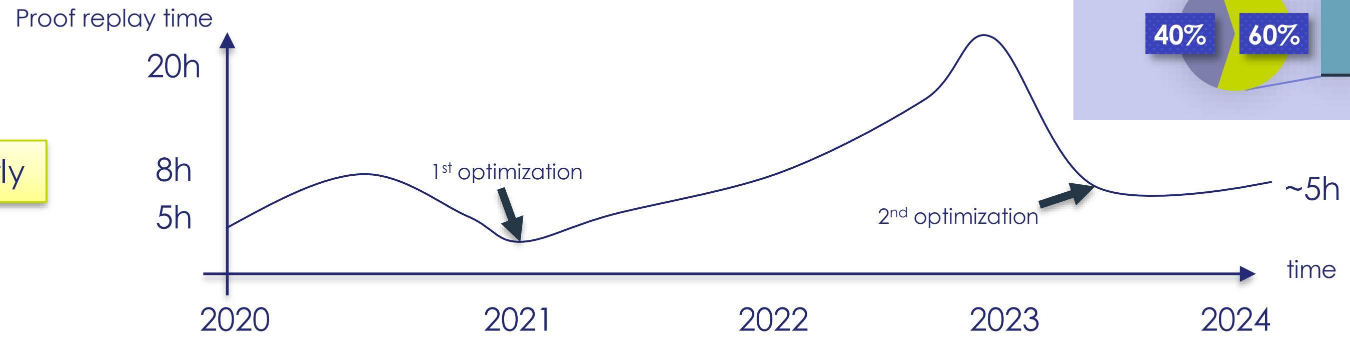
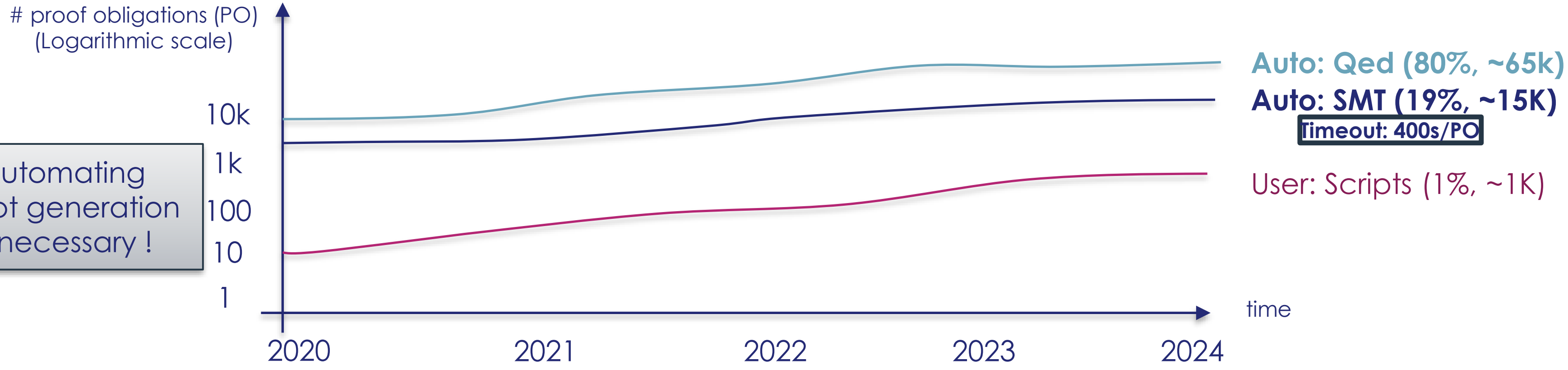
Proof effort



Costly



Automating script generation is necessary !



(TACAS 2024) Automate where Automation Fails: Proof Strategies for Frama-C/WP (jointly with CEA-List)

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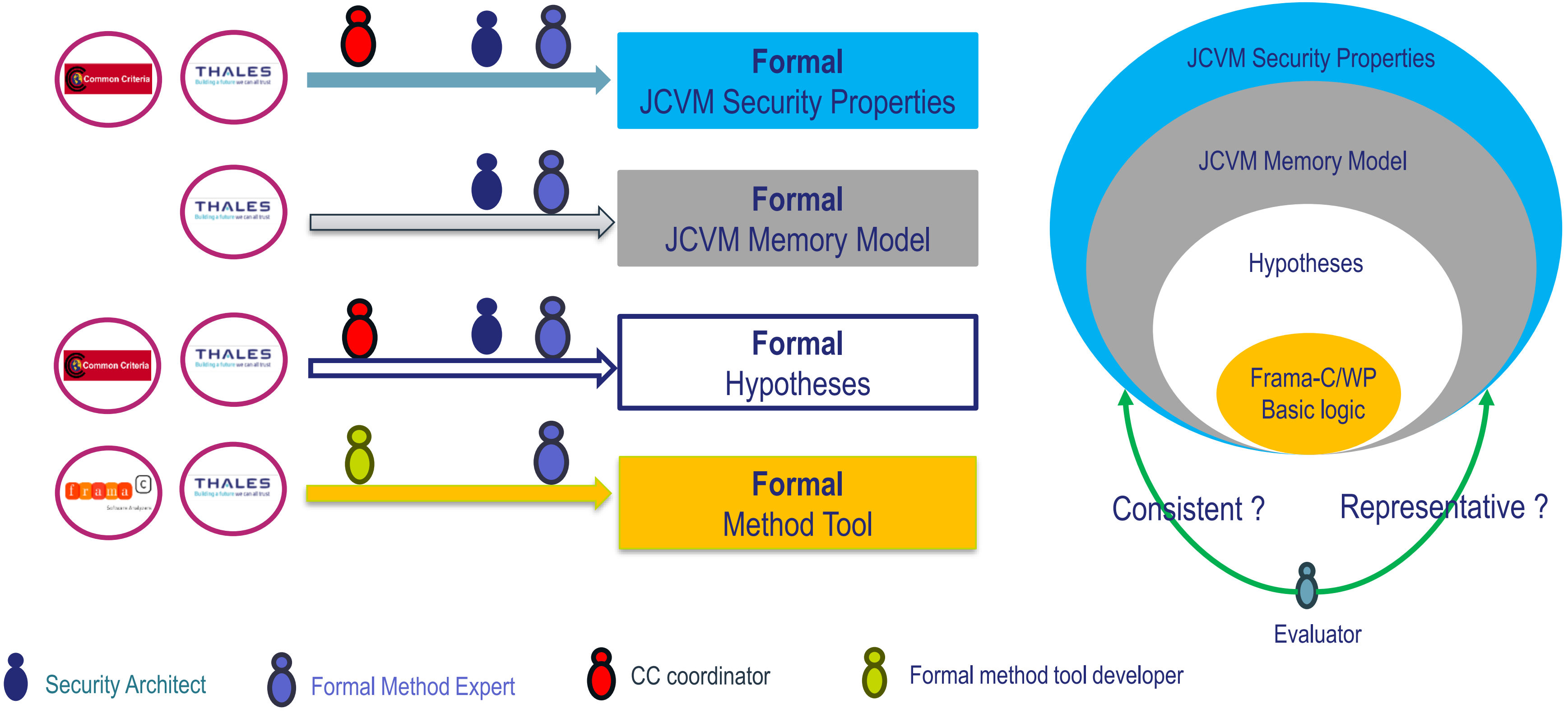
Common Criteria certification: roles distribution



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Achievements

Formal Model Expressivity

- Global security properties
- Functional properties
- Ghost code

Formal Model Representativity

- Application on source code
- Full traceability
- Limited code transformations

Verification Efficiency

- ~5h proof time
- ~80k POs
- ACSL in C Macros

Verification tool features

- MetAcsl: auto. annotations
- Enriched usage options in WP

Feedbacks from certification evaluations at Thales DIS with (CEA-Leti and ANSSI)

Good points

- **Straightforward correspondence from the security mechanisms to the formal model**
- The approach perfectly fits into the continuation of other tasks of the CC evaluation process
- Immediate understanding of formal entities (e.g. JCVM memory model)
- No refinement, thus no relation between multiple models to be evaluated
- The implementation challenges the formal model by construction

Points of attention

- **Code complexity directly transferred to the model**
- Sensitivity to tool scalability issues
- Organization of a high number of manual annotations

November 2023

August 2023

October 2022

October 2021

Ongoing and future work (for certification projects)

More expressivity

- **Handle more C features** (eg. union types, setjmp/longjmp, function pointers)
- Extend supported ACSL features (e.g. statement contracts, \from clauses)
- Combine Frama-C/WP memory models to adapt to locally used C features

More automation

- **Automatic generation of proof scripts** is required for industrial usage
- CC documentation generation (traceability of security requirements)
- Need for an IDE dedicated to C/ACSL coding and proof debugging

More efficiency

- Enhance proof parallelization
- **Enhance proof time profiling** (especially for Qed simplifications)
- Allow partial proofs as needed while updating code and specification

Formal verification of **security properties** is mature and integrated into the software engineering process.

Tool enhancements are still needed to facilitate daily usage by specification and verification engineers.

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Ongoing and Future Work, cont'd

Reasoning about metaproperties and other annotations can be helpful

- Sometime metaproperties can be deduces from other ones and ACSL annotations
- Preliminary ideas of deduction 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

- Complex programs often have parts with many properties and with low-level operations
- Some of the maintained properties are irrelevant for some properties
- More abstract levels of reasoning can be helpful
- Combining deductive verification with abstract interpretation based tools [Bernier et al, FASE 2024]

Automatic generation of global properties from a high-level specification mechanism

- Express global properties in a dedicated domain-specific language
- Generate metaproperties from it
- Create a bridge between high-level and code-level artifacts

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