Frama-C for Cybersecurity
A Few Case Studies

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Outline

1. Frama-C at a Glance
2. Main Verification Tools
   - Eva
   - Wp
   - E-ACSL
3. Advanced Security Verifications

Part I

Frama-C at a Glance

Framework for analyses of source code written in ISO 99 C

[Baudin & al, 2021]

- developed by CEA LIST since 2005
- comes with a formal specification language: ACSL
- targets both academic and industrial usage
- almost open source (LGPL 2.1)
- first open-source release (1-Hydrogen) in 2008
- last open-source release (26-Iron): yesterday!

http://frama-c.com

- also non-CEA extensions and distributions
- targets both academic and industrial usages

Several tools inside a single platform

- plug-in architecture *à la* Eclipse [Signoles, 2015]
- tools provided as plug-ins
  - 32 plug-ins in the latest open source distribution
  - outside open source plug-ins
  - close source plug-ins, either at CEA (> 20) or outside

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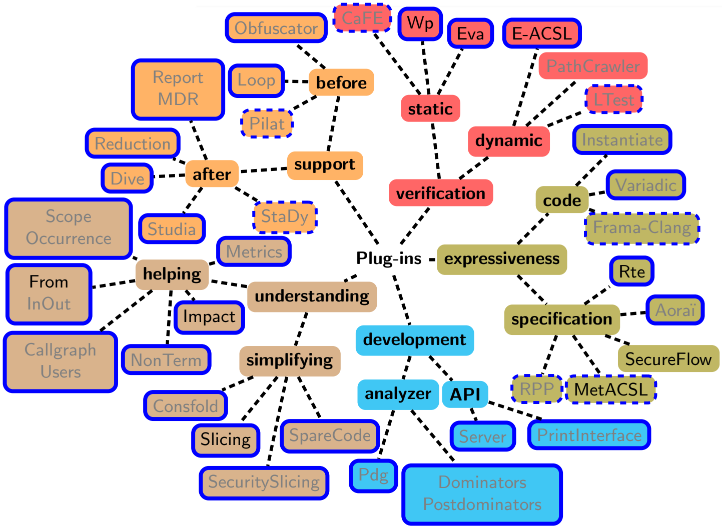
  - outside open source plug-ins
  - close source plug-ins, either at CEA (> 20) or outside
- plug-ins connected to a kernel
  - provides an uniform setting (command lines, AST, etc)
  - provides general services (data structures, etc)
  - synthesizes useful information (proved properties, etc)
  - analyzer combinations [Correnson & Signoles, 2012]

Frama-C

Plug-in Gallery



distributed within Frama-C

external and open source

close source

Frama-C

Development Platform

- developed in OCaml
- library dedicated to analysis of C code

development of plug-ins by third party

- powerful low-cost analyser
- dedicated plug-in for specific task (e.g., coding rule verifier)
- dedicated plug-in for fine-grain parameterization
- extension of existing analysers

Part II

Main Verification Tools

Domain of variations of variables of the program

- abstract interpretation
- automatic analysis
- correct over-approximation
- alarms for potential invalid operations
- alarms for potential invalid ACSL annotations
- ensures the absence of runtime error
- graphical interface: display the domain of each variable at each program point
- [Blazy et al, 2017]

Parameterization

- Eva is automatic
- but requires fine-tuned parameterization to be precise/efficient
- trade-off between time efficiency *vs* memory efficiency *vs* precision
- stubbing: `main` function and missing library function
  - either provide C code or ACSL specification (usually, `assigns`)
  - similar to stubbing required by testing
- 100+ parameters
  - require expertise
  - try `-eva-precision n` first ($0 \leq n \leq 11$)

Demo

PolarSSL

(now known as Mbed-TLS)

https://git.trustedfirmware.org/mirror/mbed-tls.git/about/

- C implementation of TLS (aka SSL)
- not as complex as openSSL

Dependency Analysis

- tied to Eva
- for each memory location `loc` possibly modified, returns its dependencies
- i.e. the set of locations whose value might be used in computing the final value of `loc`
- over-approximation: some dependencies might be spurious
- may help security audits

Example

Keccak (SHA-3)

```
> frama-c -eva -eva-slevel 1000 -deps \
          Keccak-simple.c KeccakNISTInterface.c \
          KeccakSponge.c KeccakF-1600-reference.c test.c

[from] Function rho:
  context.state[0..199]
         FROM context.state[0..199];
         KeccakRhoOffsets[0..24]; A (and SELF)
[from] Function theta:
  context.state[0..199] FROM
      context.state[0..199]; A (and SELF)
[from] Function KeccakPermutationOnWords:
  context.state[0..199] FROM
          context.state[0..199];
          KeccakRoundConstants[0..23];
          KeccakRhoOffsets[0..24]; state (and SELF)
```

Impact

- computes impact of a set S of statements
  [Monate & Signoles, 2008]
- i.e. the statements whose evaluation depend on S
  - data dependency (whether it results from a computation)
    - `x = n; y = x;`
  - address dependency (whether its memory location is impacted)
    - `p = q; *p = 0;`
  - control dependency (whether a branch may be taken)
    - `if (c) x = n; y = x;`
- exploit the Program Dependence Graph (PDG)
  - make explicit all the program dependencies
    [Ottenstein and Ottenstein, 1984]
  - Frama-C's PDG relies on Eva for infering aliasing information
- may help security audits

Slicing

- removes all statements that do not change some slicing criterion
- slicing criterion
  - value of a variable at a given point
  - truth value of an ACSL assertion
  - final state of the program
- same dependencies as impact, but used in the opposite direction (dual analysis)
- may make other analyses more tractable
- may help security audits

Wp

- based on Dijkstra's weakest preconditon calculus
- generates theorems (proof obligations) to ensure that a code satisfies its ACSL specification
- uses automatic/interactive theorem provers to verify these theorems
  - rely on Why3 as back-end
  - use Alt-Ergo by default
- is able to verify complex specifications
- modular verification
  - prove each function independently from each other
  - require no stubbing
- requires to manually add extra annotations (e.g. loop invariants)

Wp

Student Example

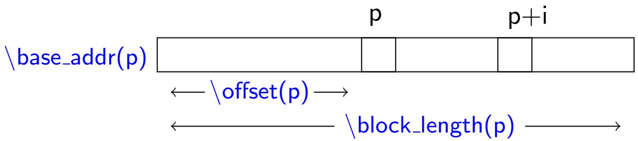
```
/*@ predicate sorted{L}(int* a, int length) =
    \forall integer i,j; 0<=i<=j<length ==> a[i]<=a[j]; */

/*@ requires \valid(a+(0..length-1));
    requires sorted(a,length);
    requires length >=0;

    assigns \nothing;
    behavior exists:
      assumes \exists integer i; 0 <= i < length && a[i] == key;
      ensures 0<=\result<length && a[\result] == key;
    behavior not_exists:
      assumes \forall integer i; 0<=i<length ==> a[i] != key;
      ensures \result == -1;
    complete behaviors;
    disjoint behaviors; */
int binary_search(int* a, int length, int key);
```

non-security oriented!

ACSL and Memory Properties

- memory properties are important for code security
- ACSL provides built-ins memory-related predicates and functions
  - `\valid(p)`: whether $*p$ has been properly allocated
  - `\valid_read(p)`: same as `\valid(p)` but p is read only (e.g., literal string)
  - `\initialize(p)`: whether $*p$ is initialized
  - `\separated(p,q)`: p and q point to disjoint memory blocks
  - 

  - ...

WP's Use Cases

- X509 parser developped by ANSSI
  - https://github.com/ANSSI-FR/x509-parser
- Wookey, secure storage device developped by ANSSI
  - https://github.com/wookey-project
  - [Benadjila et al, 2019]
- proved RTE-free by ANSSI
  - functional correctness also proved
  - combined Eva and Wp
  - X509: [Ebalard et al, 2019]
  - Wookey: [Benadjila et al, 2021]

verification of ACSL properties at runtime

- generates inline monitors for ACSL properties
  - takes as input an ACSL-annotated C program
  - generates a new C program
  - that behaves as the original C program if all the annotations are valid; or
  - fails on the first invalid annotation (by default)
  - [Signoles et al, 2017]

```
int div(int x, int y) {
  /*@ assert y-1 != 0; */
  return x / (y-1);
}
```

$\xrightarrow{\text{E-ACSL}}$

```
int div(int x, int y) {
  /*@ assert y-1 != 0; */
  e_acsl_assert(y-1 != 0L);
  return x / (y-1);
}
```

how to monitor memory-related properties, e.g. `\valid(p+i)`?

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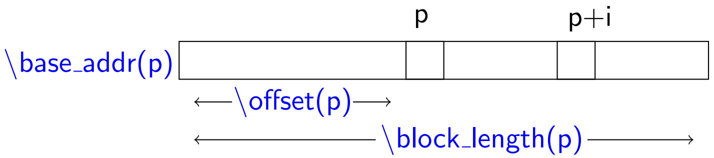


- block-level memory properties

```
char buf1[1], buf2[1];
/*@ assert \valid(buf1 + 1); */ // must fail
buf1[1] = 'a';
```

E-ACSL Expressiveness

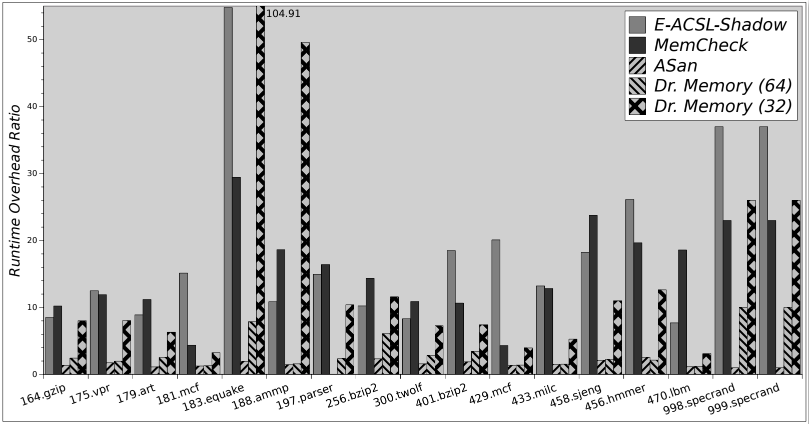
[Vorobyov et al, 2018]

Defect Type	E-ACSL	Google's Sanitizers in Clang
Dynamic Memory	94% (81/86)	78% (67/86)
Static Memory	✓ (67/67)	96% (64/67)
Pointer-related	56% (47/84)	32% (27/84)
Stack-related	35% (7/20)	70% (14/20)
Resource	99% (95/96)	60% (58/96)
Numeric	93% (100/108)	59% (64/108)
Miscellaneous	94% (33/35)	49% (17/35)
Inappropriate Code	– (0/64)	– (0/64)
Concurrency	– (0/44)	73% (32/44)
Overall	71% (430/604)	57% (343/604)

Detection Capabilities over Toyota ITC Benchmark:
more expressive than mainstream tools

E-ACSL Performance

[Vorobyov et al, 2017]



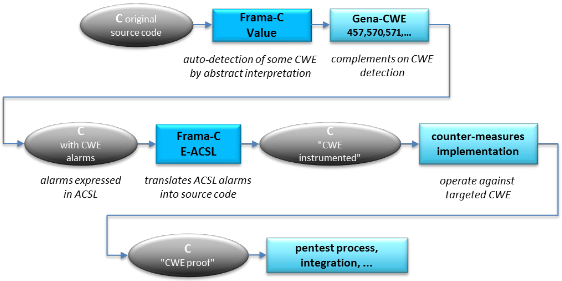
×17 time-overhead; ×2.4 memory overhead on SPEC-CPU

comparable to Valgrind; still slower than AddressSanitizer

less memory-overhead than these tools

E-ACSL

Dassault Aviation's Use Case


C original source code
Frama-C Value
Gena-CWE 457,570,571,...
auto-detection of some CWE by abstract interpretation
complements on CWE detection
C with CWE alarms
Frama-C E-ACSL
C "CWE instrumented"
counter-measures implementation
alarms expressed in ACSL
translates ACSL alarms into source code
operate against targeted CWE
C "CWE proof"
pentest process, integration, ...

first, use automatic static analysis to detect vulnerabilities;
then, switch to fast runtime monitoring

Experimented on modules from Apache / OpenSSL
[Pariente & Signoles, 2017]

Part III

Advanced Security Verifications

Test Inversion and Countermeasures

```
if (password != secret)   return 1;
if ! (password == secret) return 1;
```

- countermeasures: redundancy checks for critical sections
  - repeat critical checks at least $k+1$ time each, assuming the attacker can invert up to k tests
- prove correctness of redundant-check countermeasures
  - rely on mutation testing
- implemented in Frama-C/LTest
  - LTest is a suite of Frama-C plug-ins providing test coverage metrics
- successfully applied on Wookey
  - 1 incorrect countermeasure found
  - proved after fixing
  - [Martin et al, 2022]

MetACSL: System-Level Properties

[Robles et al, 2019]

- ACSL is a quite low-level specification language
  - difficult to express system-level properties
  - e.g. security policies
- MetACSL introduces a higher-level specification language
- MetACSL automatically converts specifications written in this language to sequences of ACSL annotations
- verify the generated annotations with standard techniques
  - WP
  - E-ACSL

MetaCSL in Practice

- example from an OS microkernel's specification:

```
/*@ meta \macro, \name(\forall_page), \arg_nb(2), ... */
// Never write to a lower confidentiality page
// outside of free
/*@ meta \prop,
  \name(confidential_write),
    \targets(\diff(\ALL, page_free, init)),
    \context(\writing),
      \forall_page(p,
        p->status == PAGE_ALLOCATED
        && user_level > page_level(p)
        ==> \separated(\written, page_data(p))
      ); */
```

- MetaCSL used for specificying and verifiying with WP the Wookey's bootloader module [Robles et al, 2021]

Common Criteria Certification

[Djoudi et al, 2021]

- Formal verification of a JavaCard Virtual Machine
- Common Criteria's EAL7 certificate
- Example of properties
  - header integrity
    - allocated object's header cannot be modified during a run
  - data integrity
    - allocated object's data can be modified only by the owner
  - data confidentiality
    - allocated object's data can be read only by the owner
- generate $\approx 400,000$ ACSL annotations from ≈ 500 MetACSL properties
  - all proved with Wp

THALES

Conclusion and Perspectives

- Frama-C provides scalable analyzers for C code verification
  - Eva: proving absence of undefined behaviors
  - Wp: proving functional properties
  - E-ACSL: checking properties at runtime
- possible to check advanced security properties
  - correctness of redundancy checks
  - system-level properties
  - but also (not shown here):
    - information flow properties [Barany and Signoles, 2017]
    - relational properties [Blatter et al, 2022]
    - privacy properties (Clouet's talk this afternoon)
    - taint analysis (ongoing work)
    - type-state analysis (ongoing work)
    - access-control policies (ongoing work)
    - ...
- usable for real-world applications
  - EAL7 certification

Software Analyzers

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