Frama-C for Code Security

Julien Signoles

Software Safety & Security Lab

Cyber in Saclay

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Outline

1. Frama-C at a Glance
2. Deductive Verification with ACSL and WP
3. Value Analysis with Eva
4. Runtime Verification with E-ACSL
5. Combining Analyses for Security-Oriented Verifications

Part I

Frama-C at a Glance

Frama-C Distribution

Framework for analyses of source code written in ISO 99 C

[Kirchner et al, 2015]

- developed by CEA LIST since 2005
- almost open source (LGPL 2.1)
- first open-source release aka Hydrogen in 2008
- last open-source release aka 22-Titanium in November 2020

http://frama-c.com

- also proprietary extensions and distributions
- targets both academic and industrial usages

Frama-C, a Collection of Tools

Several tools inside a single platform

- plug-in architecture *à la* Eclipse [Signoles, 2015]
- tools provided as plug-ins
  - 31 plug-ins in the latest open source distribution
  - outside open source plug-ins
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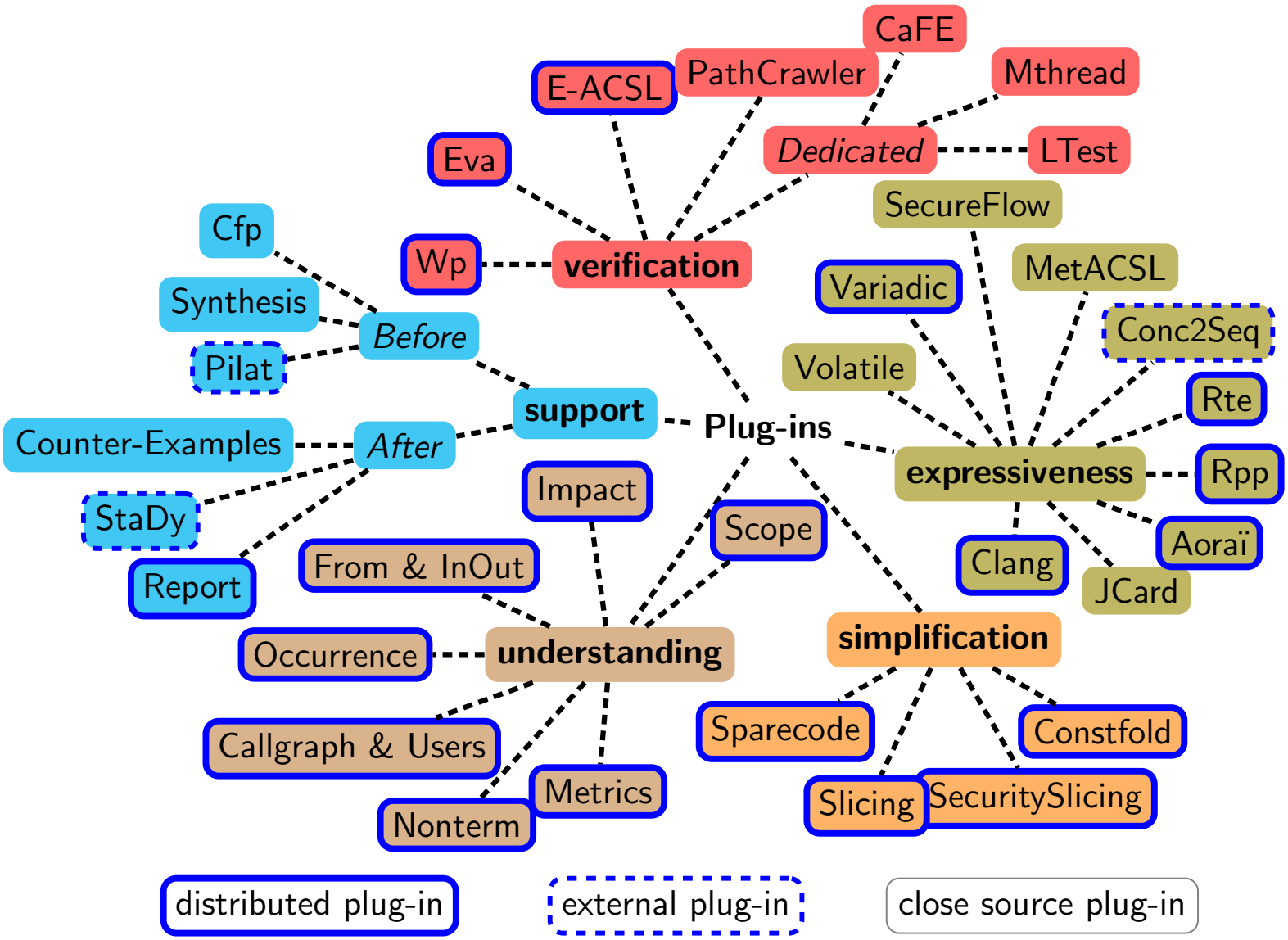
  - close source plug-ins, either at CEA (> 20) or outside
- plug-ins connected to a kernel
  - provides an uniform setting (command lines, AST, etc)
  - provides general services (data structures, etc)
  - synthesizes useful information (proved properties, etc)
  - analyzer combinations [Correnson & Signoles, 2012]

Frama-C Plug-ins Gallery



Frama-C, a Development Platform

- developed in OCaml
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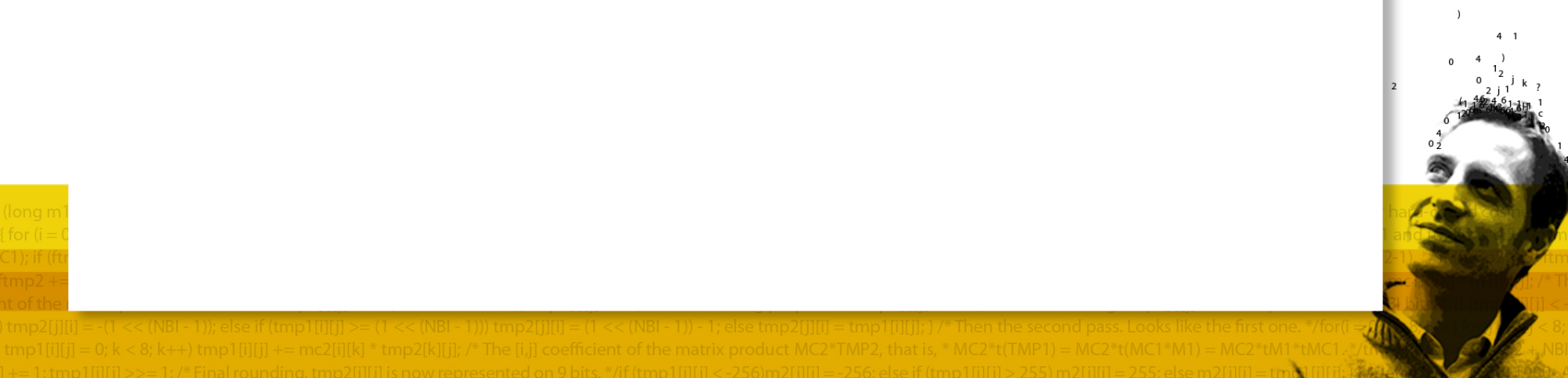
development of plug-ins by third party

- powerful low-cost analyser
- dedicated plug-in for specific task (coding rules verifier)
- dedicated plug-in for fine-grain parameterization
- extension of existing analysers

Part II

Proof of Formal Specifications with ACSL and WP



Deductive Verification in a Nutshell

Objectives

Rigorous, mathematical proof of program semantic properties

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  - if invalid, most of them lead to security vulnerabilities
- termination
  - does my program terminate (when expected)?

Deductive Verification in a Nutshell

Input/Output

- based on weakest precondition calculus [Dijkstra, 1975]
- Modular reasoning
  - handle each function independently
- input: function + precondition + postcondition
  - precondition = what the function assumes on its inputs
  - postcondition = what is guarantee as function's outputs if the precondition is satisfied
- output: does the precondition implies this property?

Deductive Verification in a Nutshell

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deductive verification is **NOT** an automatic process

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- for each loop, need to write a loop invariant that hold just before entering the loop and at the end of each iteration
- for termination, also need to write a loop variant for each loop (e.g., a nonnegative value that decreases at each loop iteration)

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- for each loop, need to write a loop invariant that hold just before entering the loop and at the end of each iteration
- for termination, also need to write a loop variant for each loop (e.g., a nonnegative value that decreases at each loop iteration)
- generate verification conditions (VC) to be proven
- relies on external provers to prove them
  - automatic provers (Alt-Ergo, Z3, CVC4, ...)
  - proof assistants (Coq, PVS, Isabelle/HOL...)

ACSL, a Formal Specification Language for C

Specifications need to be formally expressed

- formal specification language for ISO C 99
- designed by CEA LIST and Inria Toccata
- Frama-C provides a reference implementation
- like JML for Java, spec# for C# and Spark2014 for Ada
- contract-based language like Eiffel
- designed for program proving
- based on first order typed polymorphic logic
- logical terms include pure C expressions, and also mathematical integers and reals

Function Contract

Function contracts:

- precondition: `requires`
  - what is assumed on the inputs (ensured by the callers)
- postcondition: `ensures`
  - what is guaranteed by the function body (assuming the precondition)
- written left-values: `assigns`
  - which memory locations may be modified by the function

Specific keywords:

- `\result`: the returned value
- `\old(x)`: value of `x` in the pre-state
- `\at(x,l)`: value of `x` at label `l`
- `\nothing` (in `assigns`): no left-value is written

Example 1

A First Program Proof

- specify and prove the following program

```
/* returns the absolute value of x */
int abs(int x) {
  if (x >= 0) return x;
  return -x;
}
```

- prove it with Frama-C/WP and, e.g., Alt-Ergo
  - `frama-c -wp file.c`
  - `frama-c-gui -wp file.c`
- also prove the absence of undefined behaviors
  - `frama-c -wp -wp-rte file.c`

Example 1

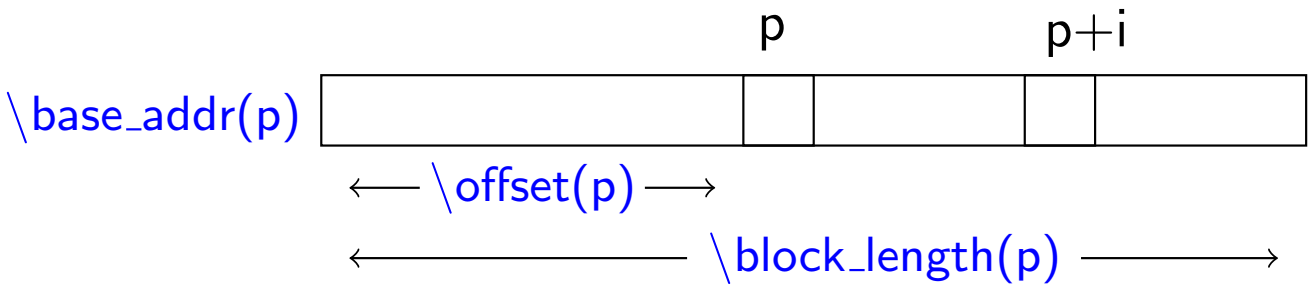
A First Program Proof

- the following specification is proved :-)

```
#include<limits.h>

/*@ requires x > INT_MIN;
  @ assigns \nothing;
  @
  @ behavior pos:
  @   assumes x >= 0;
  @   ensures \result == x;
  @
  @ behavior neg:
  @   assumes x < 0;
  @   ensures \result == -x;
  @
  @ complete behaviors;
  @ disjoint behaviors; */
int my_abs(int x) {
  if (x >= 0) return x;
  return -x;
}
```

ACSL and Memory Properties

- memory properties are important for code security
- ACSL provides built-ins memory-related predicates and functions
  - `\valid(p)`: whether $*p$ have 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
  - 

  - ...

Deductive Verification and Memory Models

- Proving memory properties requires a memory model, i.e. *"the way that the analysis tool models the storage of the underlying machine on which the code runs"* [Xu et al, 2010]

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  - if very low-level: very expressive but almost no automation
  - if very high-level: automatic proofs but poorly expressive
  - makes assumption about the code

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  - makes assumption about the code
- Frama-C/WP may handle several memory models, including:
  - Hoare: automatic proofs but allows no pointers
  - Typed: good trade-off between automation and expressiveness, yet no heterogeneous casts
  - Typed+ref: more automatic than Typed, but assumes no aliasing

Second Example

- specify and prove the following program

```
// returns the index of the minimal element
// of the given array [a] of size [length]
int find_min(int* a, int length) {
  int min = a[0], min_idx = 0;
  for (int i = 1; i < length; i++) {
    if (a[i] < min) {
      min_idx = i;
      min = a[i];
    }
  }
  return min_idx;
}
```

Second Example

solution

```
/*@ requires length > 0 && \valid(a+(0..length-1));
  @ assigns \nothing;
  @ ensures \forall integer j;
  @   0 <= j < length ==> a[\result] <= a[j];
  @ ensures 0 <= \result < length; */
int find_min(int* a, int length) {
  int min = a[0], min_idx = 0;

  /*@ loop invariant 0<=i<=length && 0<=min_idx<length;
    @ loop invariant \forall integer j;
    @   0 <= j < i ==> min <= a[j];
    @ loop invariant a[min_idx] == min;
    @ loop assigns min, min_idx, i;
    @ loop variant length - i; */
  for (int i = 1; i < length; i++) {
    if (a[i] < min) {
      min_idx = i;
      min = a[i];
    }
  }
  return min_idx;
}
```

What do you (not) prove?

- what do you prove?
  - the source code matches the spec
  - under the assumptions of your toolset
    - check the manuals, emitted warnings, ...

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- what do you prove?
  - the source code matches the spec
  - under the assumptions of your toolset
    - check the manuals, emitted warnings, ...
- what do you **not** prove?
  - the executed code does what you have in mind
    - same mistake in the code and in the spec
    - missed assumptions
    - analyzer bug: use Verasco [Jourdan, 2016]
    - compiler bug: use CompCert [Leroy, 2009]
    - hardware bug
    - ...

WP Applications

Avionic System

- used by Airbus for verifying safety properties of critical control-command code of avionic systems [Atki et al, 2018]

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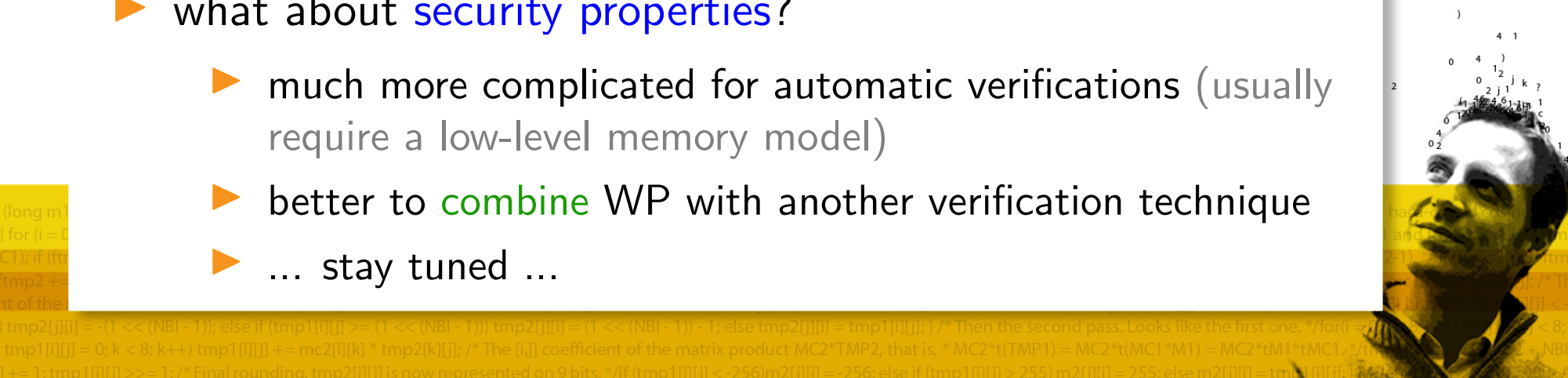
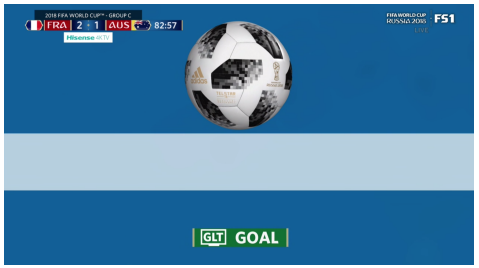
- what about security properties?
  - much more complicated for automatic verifications (usually require a low-level memory model)
  - better to combine WP with another verification technique
  - ... stay tuned ...



Part III

Value Analysis with Eva

Abstract Interpretation in two pictures



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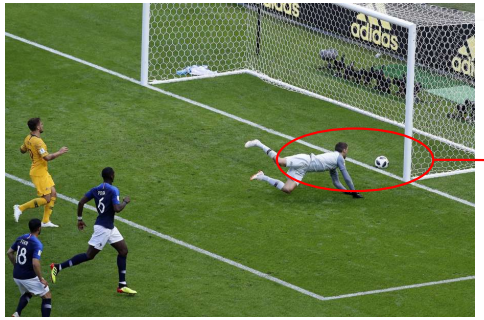

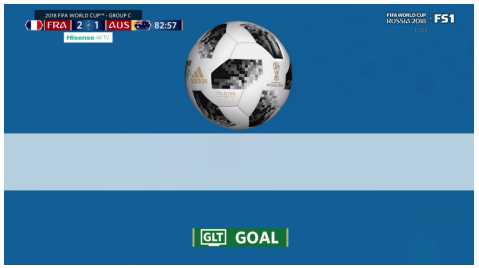

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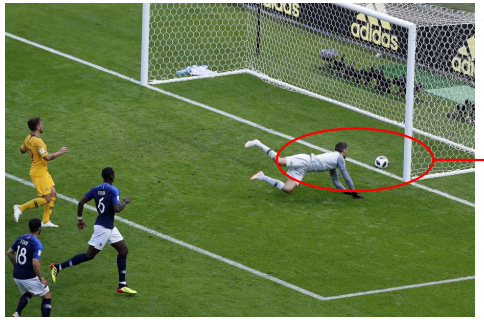

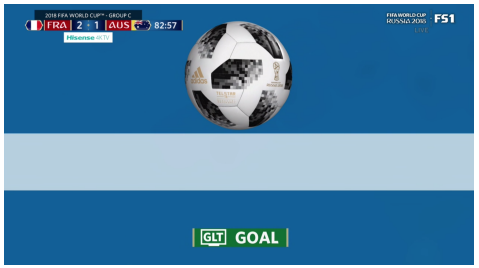

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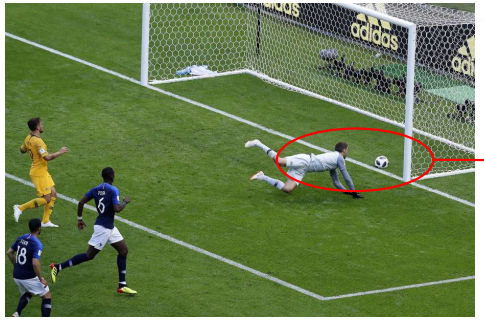

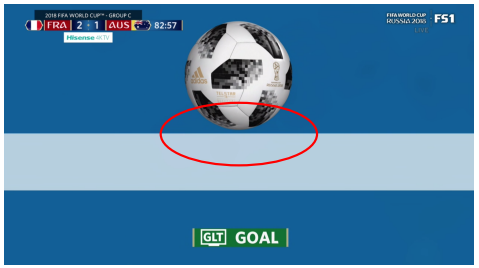

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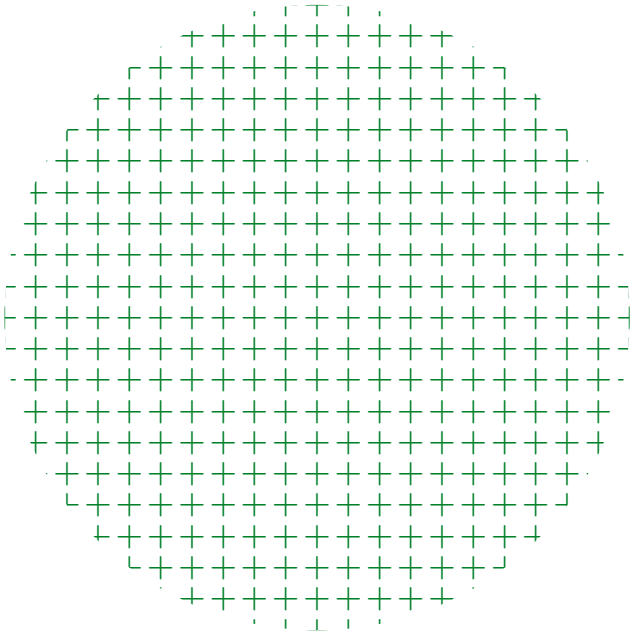
Abstract Interpretation in two pictures

Abstract interpretation is about

- abstracting away information
- ensuring answer in a reasonable time
- while retaining adequate precision
- and guaranteeing correct answers

Abstract Interpretation in a Nutshell



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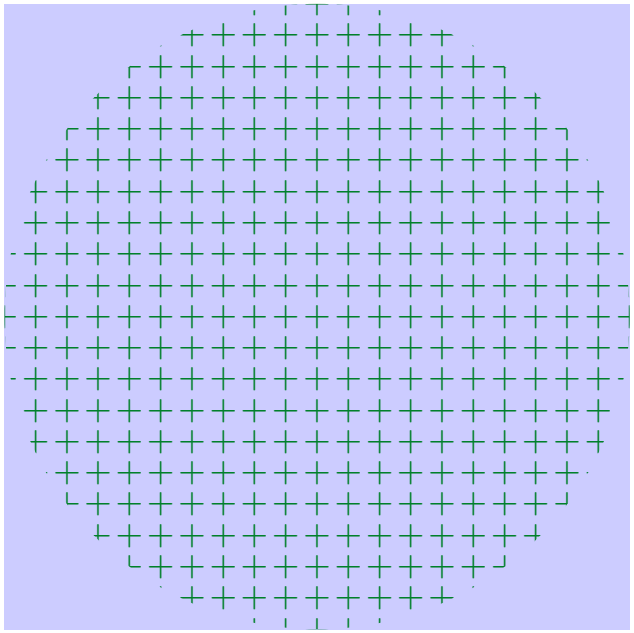

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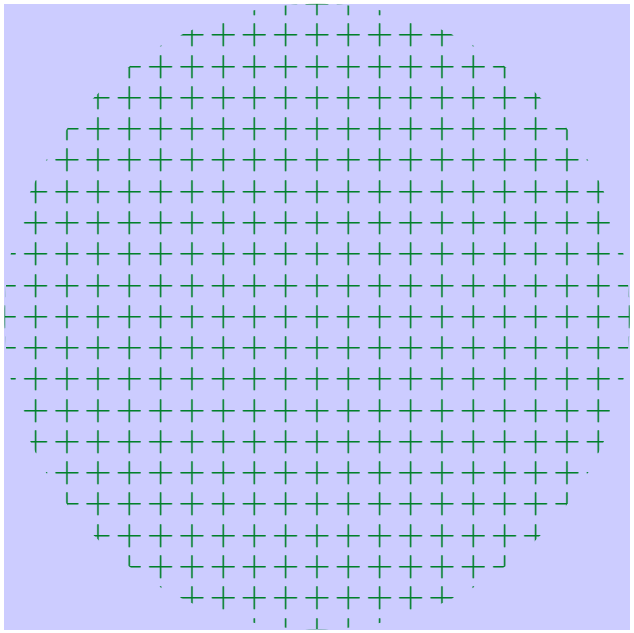

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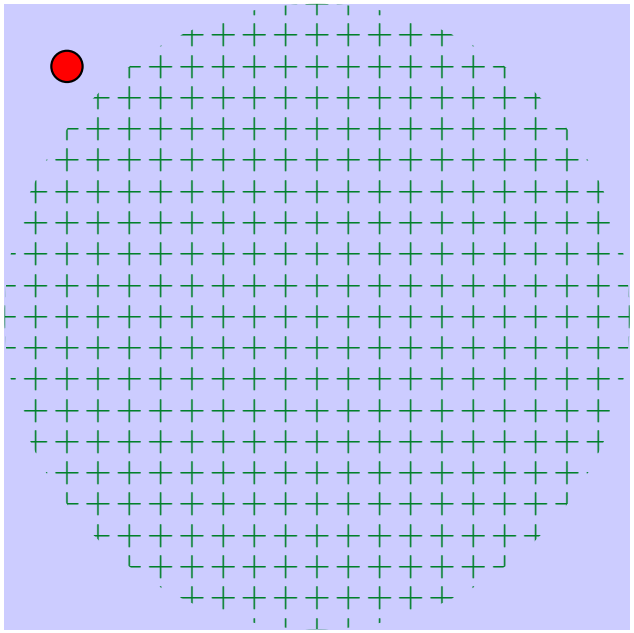

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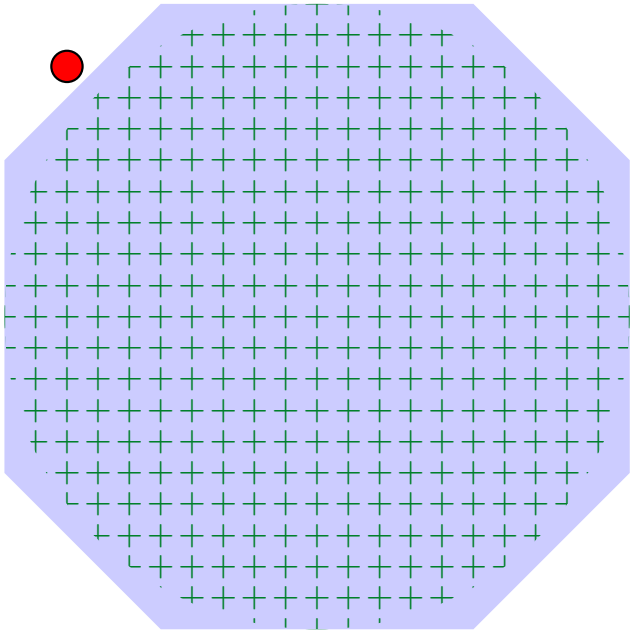

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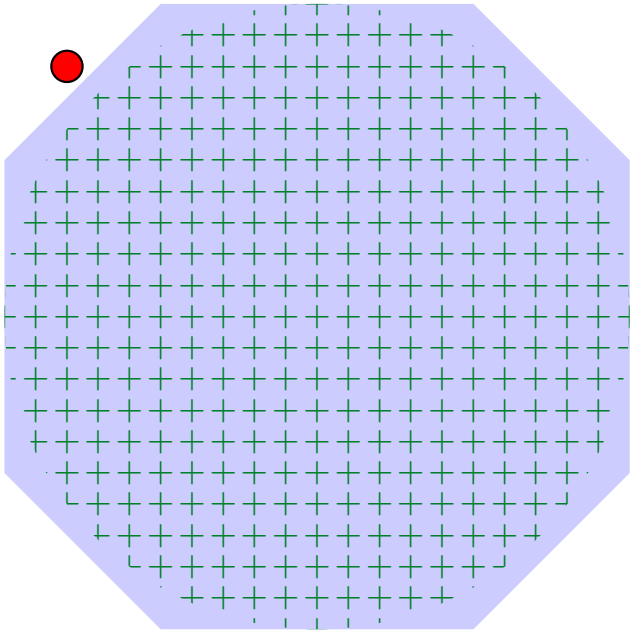

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Theoretical Foundation introduced by Cousot

[Cousot & Cousot, 77]

- One hard-wired non-relational domain
  - small sets of integers, e.g. $\{5, 18, 42\}$
  - reduced product of intervals: quick to compute, e.g. $[1..41]$
  - modulo: pretty good for arrays of structures, e.g. $[1..41], 1\%2$
  - precise representation of pointers, e.g. *32-bit aligned offset from* $\&t[0]$
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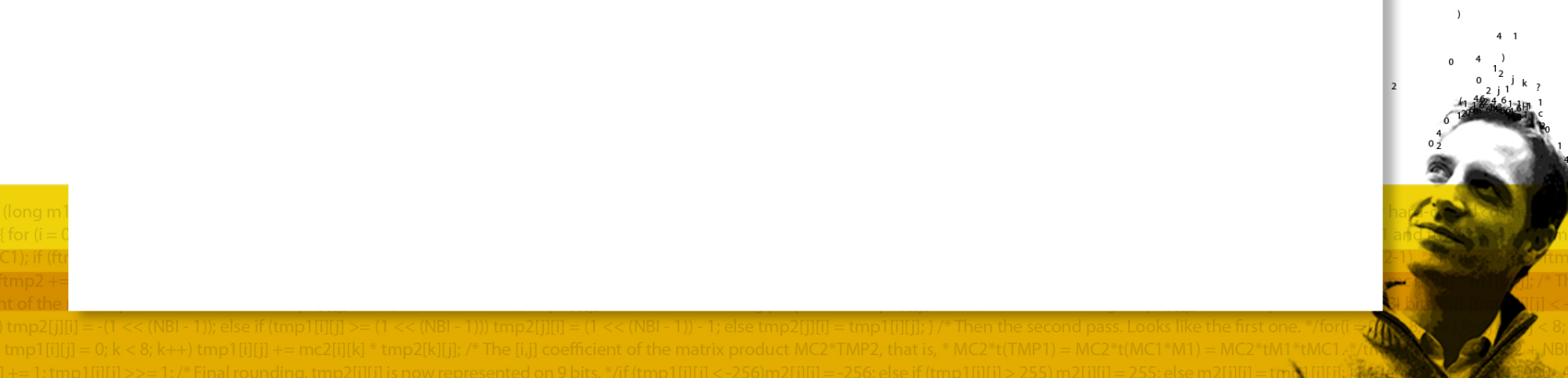
  - precise representation of pointers, e.g. *32-bit aligned offset from* $\&t[0]$
  - initialization information
- alarms on potential undefined behaviors and invalid annotations
- highly optimized
  - excellent results on embedded critical code
  - possible usage in low-level C code

- generic analysis on the abstract domain
- allow combination of abstract domains and some inter-reductions of their states [Blazy et al, 2017]
- easy to add new domain
  - Apron's domains [Jeannet & Miné, 2009]
  - gauge [Venet, 2012]
  - conditional predicate [Blazy et al, 2016]
  - numerors [Jacquemin et al, 2018]
  - ...
  - contribute yourself :-)

Eva Parameterization

- Eva is automatic
- Eva requires fine-tuned parameterization to be both precise and efficient
  - lots of parameters, but not so many almost always useful
  - try `-eva-precision n` ($0 \leq n \leq 11$)
- trade-off between time efficiency *vs* memory efficiency *vs* precision



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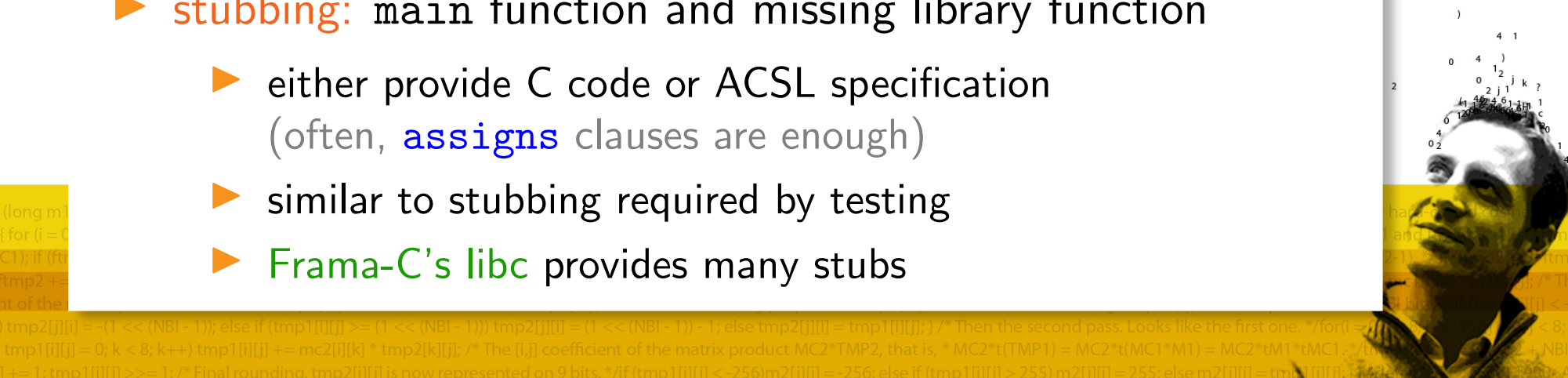
- trade-off between time efficiency *vs* memory efficiency *vs* precision
- stubbing: `main` function and missing library function
  - either provide C code or ACSL specification (often, `assigns` clauses are enough)
  - similar to stubbing required by testing
  - Frama-C's libc provides many stubs



Much more during the

practical session

Eva Applications

Scada System

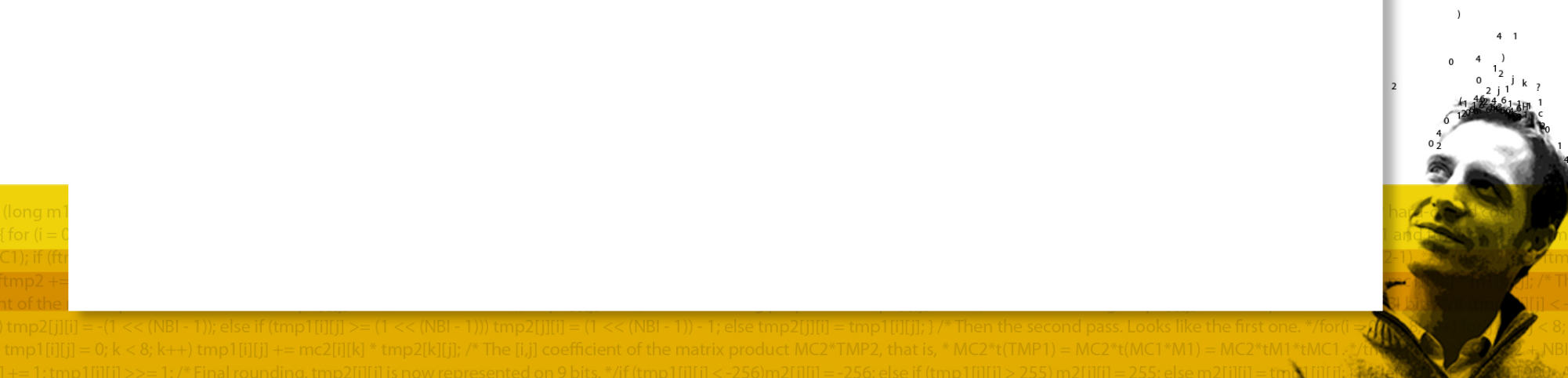
can we guarantee absence of defaults in large system-level code?

- scada systems of 100+ kloc of C code
- highest certification requirements (IEC60880 class 1)
- pinpoint the undefined behaviors and help investigate their cause
- structural properties on memory separation and cyclic behaviors
- 80% code coverage, $<$ 100 alarms
- [Ourghanlian, 2015]

frama C
Software Analyzers

Part IV

Runtime Verification with E-ACSL



Runtime Verification in a Nutshell

[Falcone et al, 2013]

- check whether a system under scrutiny satisfies a given property
- offline monitoring: after execution
- online monitoring: during execution
  - inline: the monitor is part of the system
  - outline: the monitor is outside the system
- most approaches focus on verifying temporal properties

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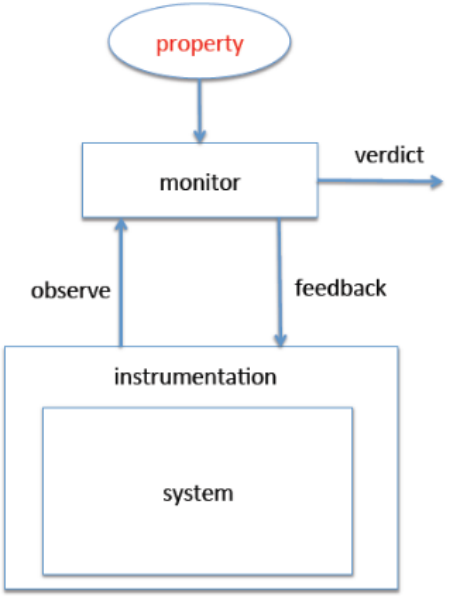
- ... yet not E-ACSL



What is E-ACSL?

- E-ACSL is a a subset of ACSL [Delahaye et al, 2013]
- E-ACSL is a Frama-C plug-in that generates inline monitors for (E-)ACSL properties on C programs [Signoles et al, 2017]
  - takes as input an (E-)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)

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

E-ACSL →

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

E-ACSL Specification Language

[Delahaye et al, 2013]

- ACSL was designed for program proving tools only
  - based on logic and mathematics
  - cannot execute any term/predicate (e.g. unbounded quantification)
  - cannot be used by dynamic analysis tools
- E-ACSL was introduced to circumvent this issue
  - a few restrictions (e.g. syntactically-bounded quantifications)
  - one semantic change: 3-valued logic with undefinedness

ACSL vs E-ACSL Semantics

The Undefinedness Problem

What is the semantics of `1/0 == 1/0`? [Cheon, 2003]

ACSL vs E-ACSL Semantics

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  - no term is undefined, even `1/0` and `*p` when `p` is null
  - predicates such as `1/0 == 1/0` are valid
  - easier to prove properties with automatic theorem provers

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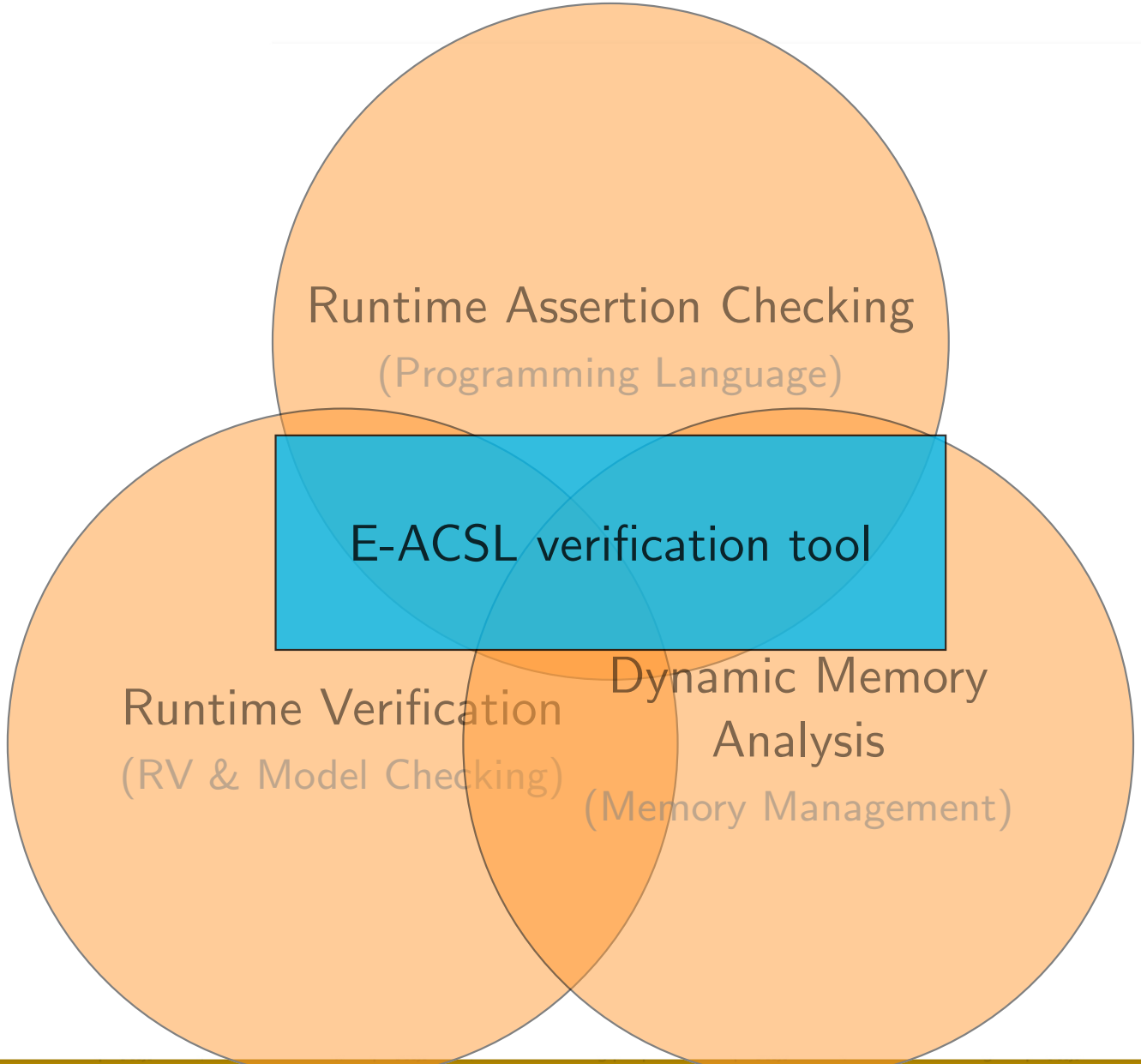
  - predicates such as `1/0 == 1/0` are valid
  - easier to prove properties with automatic theorem provers
- E-ACSL semantics is a 3-valued logic with undefined values
  - Chalin's Runtime Assertion Checking semantics [Chalin, 2009]
  - Follows the strong validity principle [Konikowska et al, 1991]
  - the semantics of 1/0 is "undefined"
  - a predicate is valid if it is both defined and true
  - at runtime, usual programming-language semantics
    - executing undefined terms is undefined behaviors

E-ACSL's Scientific Fields



Memory Monitoring

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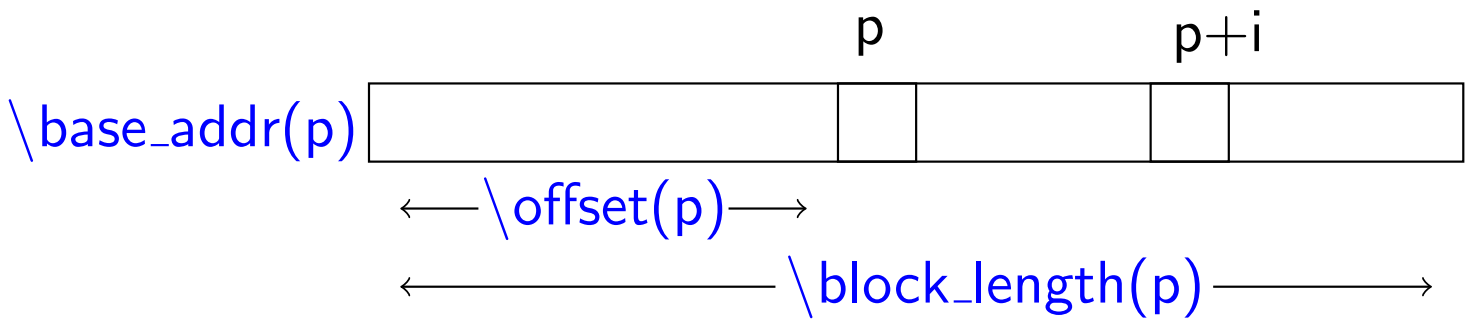
Memory Monitoring

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



- block-level memory properties

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

Dynamic Memory Analyzers

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  - extend the pointer representation with bounds information.
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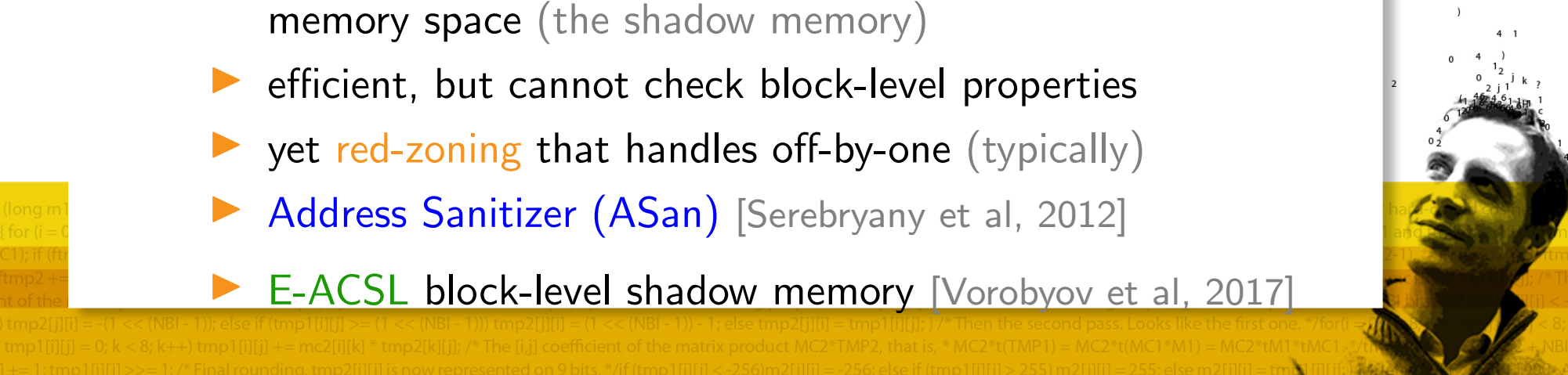
  - E-ACSL block-level shadow memory [Vorobyov et al, 2017]



E-ACSL Expressiveness

[Vorobyov et al, 2018]

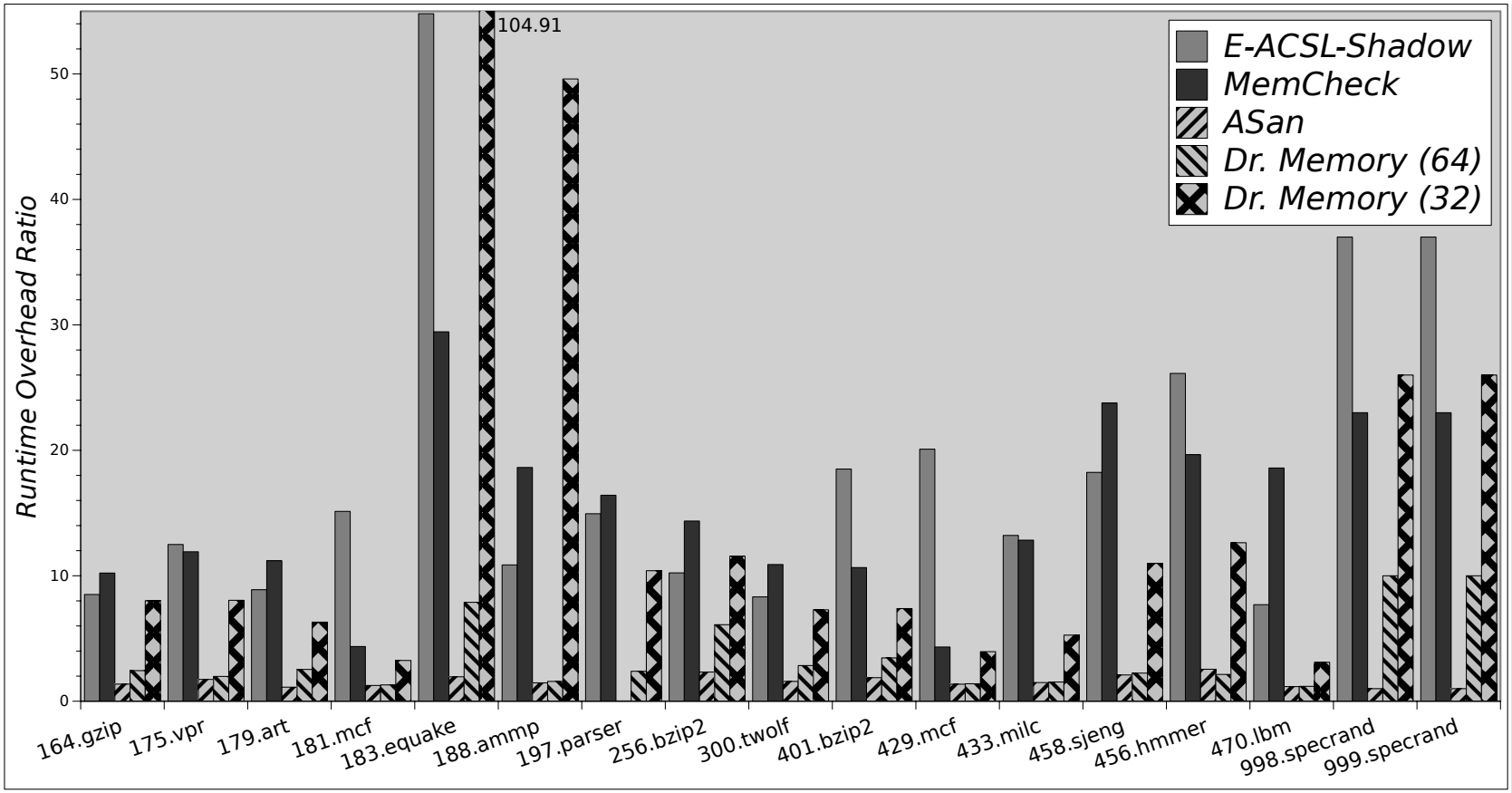
Defect Type	E-ACSL	Google's Sanitizers in Clang
Dynamic Memory	94% (81/86)	78% (67/86)
Static Memory	✓ (67/67)	96% (64/67)
Pointer-related	56% (47/84)	32% (27/84)
Stack-related	35% (7/20)	70% (14/20)
Resource	99% (95/96)	60% (58/96)
Numeric	93% (100/108)	59% (64/108)
Miscellaneous	94% (33/35)	49% (17/35)
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 the 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

Part V

Combining Analyses for Security-Oriented Verifications

Combining E-ACSL, Eva, and WP

Security-Oriented Applications

- no verification technique is perfect
  - WP is not always fully automatic
  - Eva requires fine-tuning and cannot discharge all alarms
  - E-ACSL does not check all possible inputs

Combining E-ACSL, Eva, and WP

Security-Oriented Applications

- no verification technique is perfect
  - WP is not always fully automatic
  - Eva requires fine-tuning and cannot discharge all alarms
  - E-ACSL does not check all possible inputs
- combining them can be helpful for large verification tasksr
  - Dassault Aviation combines Eva and E-ACSL for deploying security counter-measures on OpenSSL/Apache modules [Pariente & Signoles, 2017]
  - ANSSI combines Eva and WP for checking that a parser is bug-free [Ebalard et al, 2019]
  - Contiki modules were verified by ruling them all [Blanchard et al, 2018]
    Contiki is an OS for IoT systems [Dunkels et al, 2004]

Non-Interference Properties

[Goguen and Meseguer, 1982]

- confidentiality, e.g. no confidential data shall leak to a public channelé
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- confidentiality, e.g. no confidential data shall leak to a public channelé
- integrity, e.g. no untrusted input shall be propagated into an internal storage
- direct or explicit flows through direct assignments

```
lo = hi; // the secret data 'hi' directly flows to
         // the public data 'lo'
```

- indirect or implicit flows through control flows

```
if (hi) lo = 0; // the secret indirectly flows
```

- hidden channels
  - (non-)termination
  - execution time
  - ...

Information Flow Analysis

[Hedin and Sabelfeld, 2012]

how to check information flow properties?

- static analyses [Denning and Denning, 1977]
  - many type-based approaches [Volpano et al, 1996]
  - can be automatic and sound
  - practical issue: may reject programs with no flaws
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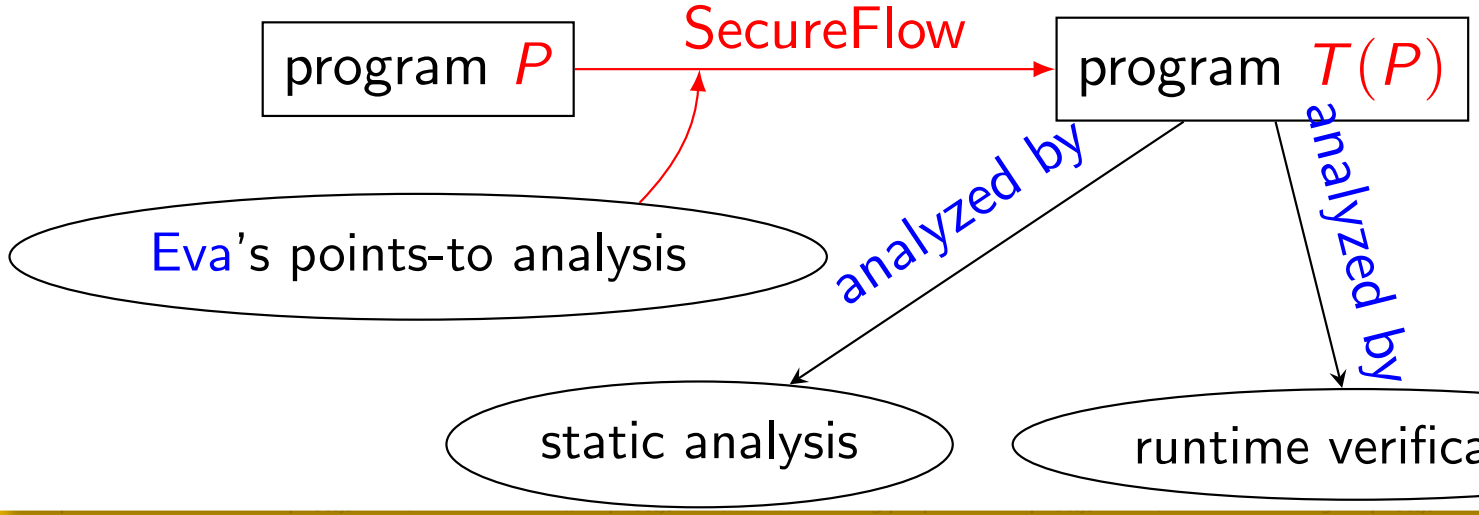
  - more precise than static approaches
  - necessarily unsound for flow-sensitive non-interference: cannot detect all incorrect flows [Russo and Sabelfeld, 2010]
- hybrid analyses [Le Guernic et al, 2006]
  - mix static and dynamic approaches
  - try to be precise while removing unsoundness

SecureFlow

(close source) Frama-C Plug-in for Information Flow Tracking

- (Termination-Insensitive) Non-Interference (TINI) properties
- hyprid approach: generates inline monitors based on static analysis for soundness in presence of pointers and aliasing [Assaf et al, 2013]
- verify the generated monitors with standard techniques
  - Eva
  - E-ACSL



SecureFlow for Time Channel Detection

[Barany & Signoles, 2017]

- may also detect some time-channel attacks
  - by checking flows of branch conditions
- experimented on LibTomCrypt (60,000-line C crypto library)
  - prove that all the 14 symmetric cryptosystems as secure
  - detect one known vulnerability in 1 asymmetric cryptosystem
    - a loop condition leaks one bit of a secret key each time it is checked
    - eventually, all bits are leaked
  - yet, detect that the patch is not fully secure

MetACSL: Expressing High-Level Properties

[Robles et al, 2019]

- ACSL is a quite low-level specification language
  - difficult to express high-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: Example

Confidentiality-oriented page management system

- modeling a security policy of a confidentiality-oriented page management system
  - MetACSL allows to model one rule at a time

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```
/*@ 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))
      ); */
```

Impact: Frama-C Plug-in for Impact Analysis

[Monate & Signoles, 2008]

- the Impact plug-in computes the "impact" of a set S of statements: help security audits
- i.e. the statements whose evaluation depend on S
  - data dependency (result of computation is impacted)

```
x = a + b; // dependencies to the definitions of a and b
```

  - address dependency (memory location is impacted)

```
*p = x; // *p depends on x (data dependency);
        // but the memory location of *p depends on p
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if (c) x = a; // x at L depends on c
L:
```

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- exploit the Frama-C's 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

Conclusion

Security Verification on C Code

- Easy, isn't it?
  - Code security is hard
  - "C is quirkly, flawed and an enormous success" [Ritchie, 1993]
  - Combining both is sometimes wtf, but always challenging :-)

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- Yet it is not the only desirable property
  - non-interference properties
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  - non-interference properties
  - correct implementation of security policies
  - constant-time implementation (Pichardie's lecture)
  - access control enforcement? Boukir's just-started postdoc
  - privacy properties? Clouet's ongoing PhD
  - ...

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Frama-C for Code Security

- Frama-C provides industrial-strengh verification tools
  - WP for deductive verification
  - Eva for abstract interpretation
  - E-ACSL for runtime verification
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- Frama-C provides many other plug-ins, including
  - SecureFlow for information flow analysis
  - MetACSL for expressing high-level properties
  - Impact for helping security audits
- Frama-C is open-source and extensible
  - feel free to develop your own plug-ins!

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