Combinations of Static and Dynamic Analyses in Frama-C: An Overview

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joint work with S.Bardin, O.Chebaro, M.Delahaye, A.Giorgetti, A.Jakobsson, J.Julliand, G.Petiot, . . .

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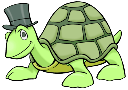
Static vs. Dynamic analysis techniques

- for a long time, seen as orthogonal and used separately
- more recently, realization of potential synergy and complementarity



Static analysis

Analyzes the source code without executing it

- Instructions reported as safe are safe (complete)
- Detected *potential* errors can be safe (imprecise)

Dynamic analysis

Executes the program on some test data

- Detected errors are really errors (precise)
- Cannot cover all executions (incomplete)

This talk presents some combinations of both approaches in Frama-C

Outline

Frama-C, a platform for analysis of C code

Detecting runtime errors by static analysis and testing (SANTE)

Deductive verification assisted by testing (STADY)

Optimizing testing by value analysis and weakest precondition (LTest)

Accelerating runtime assertion checking by static analysis (E-ACSL)

Conclusion

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Frama-C at a glance

- A Framework for Modular Analysis of C code
- Developed at CEA LIST
- Released under LGPL license
- ACSL annotation language
- Extensible plugin oriented platform
  - Collaboration of analyses over same code
  - Inter plugin communication through ACSL formulas
  - Adding specialized plugins is easy
- `http://frama-c.com/` [Kirchner et al. FAC 2015]

ACSL: ANSI/ISO C Specification Language

- Based on the notion of contract, like in Eiffel, JML
- Allows users to specify functional properties of programs
- Allows communication between various plugins
- Independent from a particular analysis
- Manual at `http://frama-c.com/acsl`

Basic Components

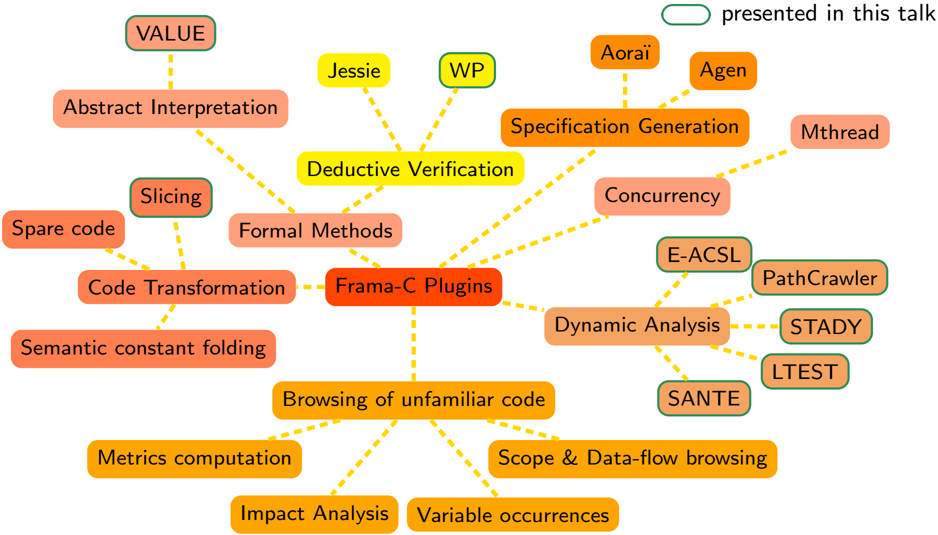
- First-order logic
- Pure C expressions
- C types + $\mathbb{Z}$ (integer) and $\mathbb{R}$ (real)
- Built-in predicates and logic functions particularly over pointers: `\valid(p)` `\valid(p+0..2)`, `\separated(p+0..2,q+0..5)`, `\block_length(p)`

Example: 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 in Frama-C/WP

Main plugins



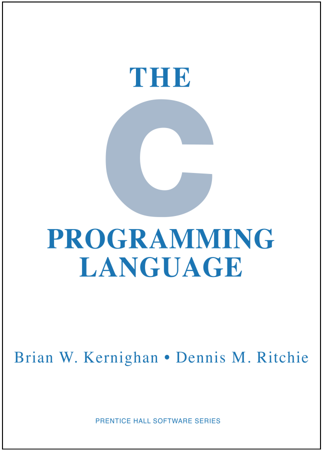
Outline

The C language is risky!

- Low-level operations
- Widely used for critical software
- Lack of security mechanisms

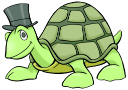
Runtime errors are common:

- Division by 0
- Invalid array index
- Invalid pointer
- Non initialized variable
- Out-of-bounds shifting
- Arithmetical overflow
- ...



SANTE: Goals

Detection of runtime errors: two approaches



Static analysis

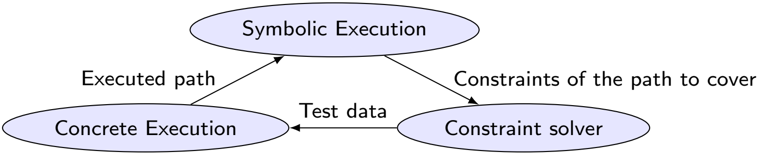
Issue: leaves unconfirmed errors that can be safe

Testing

Issue: cannot detect all errors if test coverage is partial

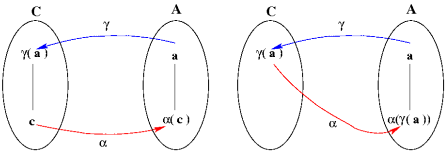
Goal: Combine both techniques to detect runtime errors more efficiently

Plugin PathCrawler for test generation



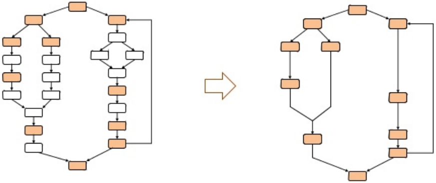
- Performs Dynamic Symbolic Execution (DSE)
- Automatically creates test data to cover program paths (explored in depth-first search, [Botella et al. AST 2009])
- Uses code instrumentation, concrete and symbolic execution, constraint solving
- Exact semantics: doesn't approximate path constraints
- Similar to PEX, DART/CUTE, KLEE, SAGE, etc.
- Online version: `pathcrawler-online.com`

Plugin “VALUE” for value analysis



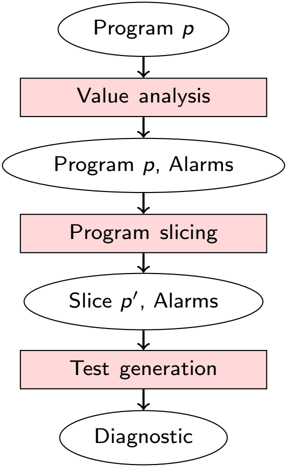
- Based on abstract interpretation [Cousot, POPL 1977]
- Computes an overapproximation of sets of possible values of variables at each instruction
- Considers all possible executions
- Reports alarms when cannot prove absence of errors

Plugin Slicing



- Simplifies the program using control and data dependencies
- Preserves the executions reaching a point of interest (*slicing criterion*) with the same behavior
- Example of slicing criteria: instructions, annotations (alarms), function calls and returns, read and write accesses to selected variables. . .

SANTE: Methodology for detection of runtime errors



- Value analysis detects alarms
- Slicing reduces the program (w.r.t. one or several alarms)
- Testing (PathCrawler) is used to generate tests on a reduced program to diagnose alarms (after adding error branches to trigger errors)
- Diagnostic
  - bug if a counter-example is generated
  - if not, and all paths were explored, the alarm is safe
  - otherwise, unknown

SANTE: Experiments

- 9 benchmarks with known errors (from Apache, libgd, . . .)

Alarm classification:

- all known errors found by SANTE
- SANTE leaves less unclassified alarms than VALUE (by 88%) or PathCrawler (by 91%) alone

Program reduction:

- 32% in average, up to 89% for some examples
- program paths in counter-examples are in average 19% shorter

Execution time:

- Average speedup w.r.t. testing alone is 43% (up to 98% for some examples)

[Chebaro et al. TAP 2009, TAP 2010, SAC 2012, ASEJ 2014]

Application to security

Program p
↓
Value & Taint analysis
↓
Program p, Alarms
↓
Program slicing
↓
Slice p', Alarms
↓
Fuzz testing
↓
Diagnostic

- Reused in EU FP7 project STANCE (CEA LIST, Dassault, Search Lab, FOKUS,...)
- Taint analysis to identify most security-relevant alarms
- Fuzz testing (Flinder tool) for efficient detection of vulnerabilities
- Applied to the recent Heartbleed security flaw (2014) in OpenSSL, other case studies in progress
- [Kiss et al., Submitted 2015]

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Plugin WP for deductive verification

$$\dfrac{\{A \wedge b\}\ c\ \{B\} \qquad \dfrac{(A \wedge \neg b) \Rightarrow B}{\{(A \wedge \neg b)\}\ \mathtt{skip}\ \{B\}}}{\dfrac{\{A\}\ \mathtt{if}\ b\ \mathtt{then}\ c\ \mathtt{else}\ \mathtt{skip}\ \{B\}}{\{A\}\ \mathtt{if}\ b\ \mathtt{then}\ c\ \{B\}}}$$

- Based on Weakest Precondition calculus [Dijkstra, 1976]
- Proves that a given program respects its specification

The enemy: proof failures, i.e. unproven properties

- can result from very different reasons
  - an error in the code,
  - an insufficient precondition,
  - a too weak subcontract (e.g. loop invariant, callee's contract),
  - a too strong postcondition,...
- often require costly manual analysis

Example: 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 in Frama-C/WP

Example: An erroneous version

```
/*@ 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 assigns k;
      loop variant n-k;
  */
  for(k = 0; k < n; k++)
    if (t[k] != 0)
      return 0;
  return 1;
}
```

Postcondition unproven. . .

. . . because of a missing loop invariant.

The reason could also be a wrong precond, or postcond., or code

STADY: Goals

- Help the validation engineer to understand and fix the proof failures
- Provide a counter-example to illustrate the issue
- Do it automatically and efficiently

STADY: Methodology for diagnosis of proof failures

- Define three kinds of proof failures:
  - non-compliance (between the code and its specification)
  - subcontract weakness (for a loop or a called function)
  - prover incapacity
- Perform dedicated instrumentation allowing to detect non-compliances and subcontract weaknesses
- Apply testing (PathCrawler) to try to find a counter-example and to classify the proof failure
- Indicate a more precise feedback (if possible, with a counter-example) to help the user to understand and to fix the proof failure

STADY: Initial experiments

- 20 annotated (provable) programs (from [Burghardt, Gerlach])
- 928 mutants generated (erroneous code, erroneous or missing annotation)
- STADY is applied to classify proof failures

Alarm classification:

- STADY classified 97% proof failures

Execution time: comparable to WP

- WP takes in average 2.6 sec. per mutant (13 sec. per unproven mutant)
- STADY takes in average 2.7 sec. per unproven mutant

Partial coverage:

- Testing with partial coverage remains efficient in STADY

[Petiot et al. TAP 2014, SCAM 2014, Submitted 2015]

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Context: white-box testing

- Generate a test input
- Run it and check for errors
- Estimate coverage: if enough, then stop, else loop

Coverage criteria (decision, mcdc, mutants, etc.) play a major role

- generate tests, decide when to stop, assess quality of testing

The enemy: Uncoverable test objectives

- waste generation effort, imprecise coverage ratios
- cause: structural coverage criteria are ... structural
- detecting uncoverable test objectives is undecidable

Recognized as a hard and important issue in testing

- no practical solution, not so much work (compared to test gen.)
- **real pain** (e.g. aeronautics, mutation testing)

LTest: Goals

We focus on white-box (structural) coverage criteria

Automatic detection of uncoverable test objectives

- a *sound* method
- applicable to a large class of coverage criteria
- strong detection power, reasonable speed
- rely as much as possible on existing verification methods

Note. The test objective "reach location *loc* and satisfy predicate *p*" is uncoverable $\Leftrightarrow$ the assertion `assert (`$\neg p$`);` at location *loc* is valid

Example: program with two uncoverable test objectives

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
  int res;
  if(x+a >= x)
    res = 1;    // the only possible outcome
  else
    res = 0;
 // l1: res == 0
 // l2: res == 2
}
```

Example: program with two valid assertions

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0
 //@ assert res != 2
}
```

Example: program with two valid assertions

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
  int res;
  if(x+a >= x)
    res = 1;    // the only possible outcome
  else
    res = 0;
 //@ assert res != 0     // both VALUE and WP fail
 //@ assert res != 2     // detected as valid
}
```

LTest Methodology: Combine VALUE $\oplus$ WP

Goal: get the best of the two worlds

- Idea: VALUE passes to WP the global information that WP needs

Which information, and how to transfer it?

- VALUE computes variable domains
- WP naturally takes into account assumptions (`assume`)

Proposed solution:

- **VALUE exports computed variable domains in the form of WP-assumptions**

Example: alone, both VALUE and WP fail

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {



  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0     // both VALUE and WP fail

}
```

Example: VALUE⊕WP

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
 //@ assume 0 <= a <= 20
 //@ assume 0 <= x <= 1000 // VALUE inserts domains...
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0

}
```

Example: VALUE⊕WP

```
int main() {
  int a = nondet(0 .. 20);
  int x = nondet(0 .. 1000);
  return g(x,a);
}
int g(int x, int a) {
 //@ assume 0 <= a <= 20
 //@ assume 0 <= x <= 1000 // VALUE inserts domains...
  int res;
  if(x+a >= x)
    res = 1;     // the only possible outcome
  else
    res = 0;
 //@ assert res != 0        // ...  and WP succeeds!

}
```

LTest: Results and Experiments

- automatic, sound and generic method
- new combination of existing verification techniques
- experiments for 12 programs and 3 criteria (CC, MCC, WM):
  - strong detection power (95%),
  - reasonable detection speed ($\leq$ 1s/obj.),
  - test generation speedup (3.8x in average),
  - more accurate coverage ratios (99.2% instead of 91.1% in average, 91.6% instead of 61.5% minimum)

[Bardin et al. ICST 2014, TAP 2014, ICST 2015]

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E-ACSL Language

Executable subset of ACSL:

- it is verifiable in finite time, suitable for runtime assertion checking
- limitations: only bounded quantification, no axioms, no lemmas
- Includes builtin memory-related predicates, for a pointer *p*:

Builtin predicate	Description
`\valid(p)`	*p* is a valid pointer
`\initialized(p)`	$*p$ has been initialized
`\block_length(p)`	Length of *p*'s memory block
`\base_address(p)`	Base address of *p*'s memory block
`\offset(p)`	Offset of *p* in its memory block

[Delahaye et al. SAC 2013]

E-ACSL plugin

The E-ACSL plugin is a runtime verification tool for E-ACSL specifications:

- it translates annotated program p into another program p'
- p' exits with error message if an annotation is violated
- otherwise p and p' have the same behavior

Example: a C program annotated with ACSL

```
int a[] = {1,2,3,4}, len = 4, i, *a_inv;




/*@ assert len > 0 ; */

a_inv = malloc(sizeof(int)*len);
for (i = len - 1; i >= 0; i--) {
  /*@ assert \valid(a + i) ; */


  a_inv[len - i - 1] = a[i];  // array a inversed
}
free(a_inv);
```

Instrumented program (simplified)

```
int a[] = {1,2,3,4}, len = 4, i, *a_inv;




/*@ assert len > 0 ; */
e_acsl_assert(len > 0);
a_inv = malloc(sizeof(int)*len);
for (i = len - 1; i >= 0; i--) {
  /*@ assert \valid(a + i) ; */
  int __e_acsl_valid = __valid(a + i, sizeof(int));
  e_acsl_assert(__e_acsl_valid);
  a_inv[len - i - 1] = a[i];
}
free(a_inv);
```

Memory monitoring in E-ACSL

- The memory model of E-ACSL should contain all live allocations of the input program, with the necessary metadata
- E-ACSL runtime support library offers primitives to store and query such metadata
- All (de)allocations are instrumented with a call to the library

[Kosmatov et al. RV 2013; Jakobsson et al. SAC 2015]

Instrumented program with full memory monitoring

```
int a[] = {1,2,3,4}, len = 4, i, *a_inv;
__store_block(a,16);
__store_block(& len,4);
__store_block(& i,4);
__store_block(& a_inv,4);
/*@ assert len > 0 ; */
e_acsl_assert(len > 0);
a_inv = __e_acsl_malloc(sizeof(int)*len);
for (i = len - 1; i >= 0; i--) {
  /*@ assert \valid(a + i) ; */
  int __e_acsl_valid = __valid(a + i,sizeof(int));
  e_acsl_assert(__e_acsl_valid);
  a_inv[len - i - 1] = a[i];
}
__e_acsl_free(a_inv);
__delete_block(& a_inv);
__delete_block(& i);
__delete_block(& len);
__delete_block(a);
```

E-ACSL Static Analysis [Jakobsson et al, JFLA 2015]

Issue: monitoring is costly

- memory monitoring
- use of GMP to deal with mathematical integers

Goal: avoid unnecessary expensive instrumentation

- memory monitoring: annotations do not necessarily evaluate each memory location
- integers: often possible to use C integral types

Solution: static analysis to reduce the instrumentation

- backward data-flow analysis to compute an over-approximation of the set of variables that must be monitored
- (sub-)typing systerm to compute the smallest type which an integer fits in

Instrumented program with full memory monitoring

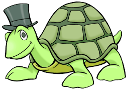
```
int a[] = {1,2,3,4}, len = 4, i, *a_inv;
__store_block(a,16);
__store_block(& len,4);
__store_block(& i,4);
__store_block(& a_inv,4);
/*@ assert len > 0 ; */
e_acsl_assert(len > 0);
a_inv = __e_acsl_malloc(sizeof(int)*len);
for (i = len - 1; i >= 0; i--) {
  /*@ assert \valid(a + i) ; */
  int __e_acsl_valid = __valid(a + i,sizeof(int));
  e_acsl_assert(__e_acsl_valid);
  a_inv[len - i - 1] = a[i];
}
__e_acsl_free(a_inv);
__delete_block(& a_inv);
__delete_block(& i);
__delete_block(& len);
__delete_block(a);
```

Instrumented program after pre-analysis

```
int a[] = {1,2,3,4}, len = 4, i, *a_inv;
__store_block(a,16);
__store_block(& len,4);
__store_block(& i,4);
__store_block(& a_inv,4);
/*@ assert len > 0 ; */
e_acsl_assert(len > 0);
a_inv = __e_acsl_malloc(sizeof(int)*len);
for (i = len - 1; i >= 0; i--) {
  /*@ assert \valid(a + i) ; */
  int __e_acsl_valid = __valid(a + i,sizeof(int));
  e_acsl_assert(__e_acsl_valid);
  a_inv[len - i - 1] = a[i];
}
__e_acsl_free(a_inv);
__delete_block(& a_inv);
__delete_block(& i);
__delete_block(& len);
__delete_block(a);
```

Outline

Conclusion

- Combining Static and Dynamic analyses can be beneficial for various domains of software verification:
  - detection of runtime errors and security vulnerabilities,
  - deductive verification,
  - runtime assertion checking,
  - test generation, ...
- Both ways: static helps dynamic and dynamic helps static
- Frama-C provides a rich and extensible framework for combined analyses

Future Work

- Frama-C++ (FP7 Stance)
- Value (ANR Vecolib)
- WP: memory model
- Solver mixing SMT & constraints (ANR Soprano)
- E-ACSL: improving efficiency and additional constructs
- PathCrawler: memory model
- Information Flow (ANR AnaStaSec)
- Reducing the gap between models/systems and code
- ...