FEDERAL UNIVERSITY OF AMAZONAS
INSTITUTE OF COMPUTING
GRADUATE PROGRAM IN COMPUTER SCIENCE

MEMORY MANAGEMENT TEST-CASE GENERATION OF C PROGRAMS USING BOUNDED MODEL CHECKING

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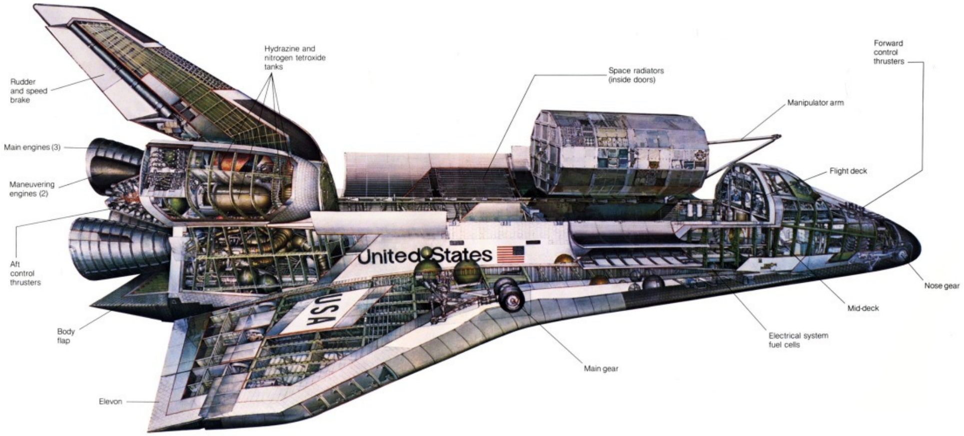
and Lucas Cordeiro

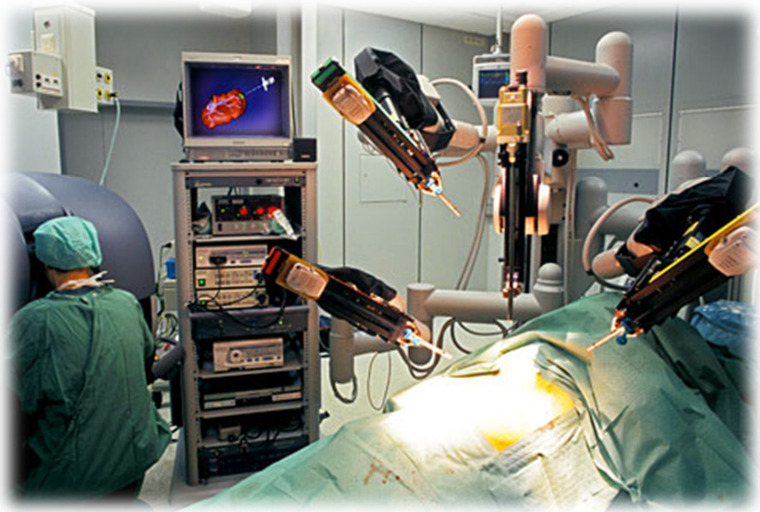
SEFM'2015

Agenda

1. Introduction
2. Background
3. Proposed Method
4. Experimental Evaluation
5. Conclusions and Future Work

Software Applications





Verification and Testing Software

In **software testing:**

- ✓ a significant human effort is required to generate effective test cases
- ✓ subtle bugs are difficult to detect

In **software model checking**:

- ✓ limited scalability to large software
- ✓ missing tool-supported integration into the development process

Verification and Testing Software

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In **software model checking**:

- ✓ limited scalability to large software
- ✓ missing tool-supported integration into the development process

The integration aims to alleviate the weaknesses from those strategies

What do you need to check?

- ✓ Analyzing **memory management** is an important task to avoid **unexpected behavior of the program**

- ✓ Pointer safety violation results in an invalid address
  - Produce an **incorrect result** of the program and not necessarily a crash

- ✓ Memory leaks have a negative impact in other application running on the same system
  - they typically **remain unobserved until** they consume a large portion of the memory

And what are we proposing? **The Map2Check Method**

- ✓ Map2Check generates automatically:
  - **memory management test cases** for structural unit tests for C programs
  - assertions from **safety properties** generated by **BMC tools**

- ✓ Map2Check aims to improve the unit testing environment, adopting features from (bounded) model checkers

- ✓ Map2Check adopts **source code instrumentation to:**
  - monitor the program's executions
  - validate assertions with **safety properties**

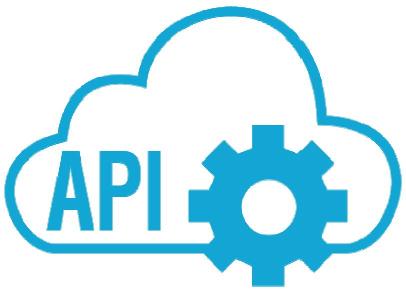
And what are we proposing? **The Map2Check Method**

Map2Check method **checks** the program **out of the BMC tools flow**

- ✓ It is based on dynamic analysis and assertion verification
- ✓ The assertions contain a set of specifications
- ✓ The **BMC is adopted as verification condition** (VC) generator that translates a program fragment and its correctness property into logical formula

The motivation of this work - **Map2Check**

- ✓ Aims to check for properties related to **pointer safety, memory leaks, and invalid free**
- ✓ Provides trace of memory addresses, in case of property violation
- ✓ Support the **integration between testing and verification** in an environment, where a software engineer can extend the analysis of the program through **APIs** and include new BMC and unit testing tools



#include <map2check.h>

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Efficient SMT-Based Bounded Model Checking - ESBMC

ESBMC is a bounded model checker for embedded ANSI-C software based on SMT (Satisfiability Modulo Theories) solvers, which allows:

- ✓ Out-of-bounds array indexing;
- ✓ Division by zero;
- ✓ Pointers safety
- ✓ Dynamic memory allocation;
- ✓ Data races;
- ✓ Deadlocks;
- ✓ Underflow e Overflow;

Safety Property

- ✓ Informally, a property in linear-time specifies the allowable (or desired) behavior of a system

- ✓ In this study, we use ESBMC VCs generator to check for memory safety as follows:
  - checking for safety pointers - **SAME OBJECT**
  - if a pointer is NULL or invalid object - **INVALID POINTER**
  - VCs for dynamic memory allocation - **IS DYNAMIC OBJECT**
  - if the argument to any free, or dereferencing operation is still a valid object - **VALID OBJECT**

Software Testing

- ✓ A **test case** consists of a test data analysis associated with an expected result of the software specification

- ✓ **Unit tests** are typically written based on a set of **test cases** to ensure that the program meets its design and behaves as expected

- ✓ We create **unit tests to analyze the software specification** together with their test data

- ✓ We adopt the **CUnit framework** to develop unit tests

Available at: http://cunit.sourceforge.net

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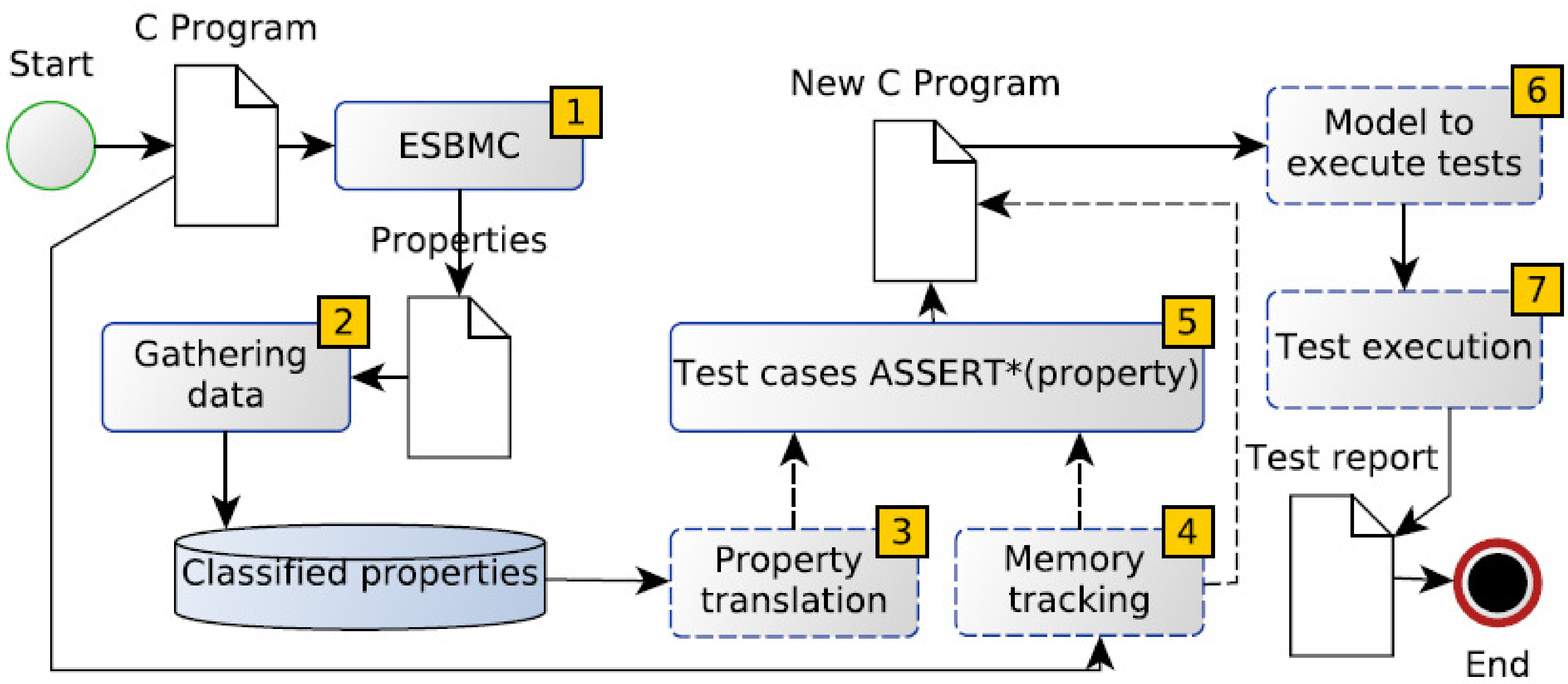
Memory Management Test Case Generation for C Programs - Map2Check



Map2Check tool2 is available at https://sites.google.com/site/map2check/

Memory Management Test Case Generation for C Programs - Map2Check

```c
int *a, *b;
int n;

#define BLOCK_SIZE 128

void foo (){ ... }

int main ()
{
  n = BLOCK_SIZE;
  a = malloc (n * sizeof(*a));
  b = malloc (n * sizeof(*b));
  *b++ = 0;
  foo ();
  if (b[-1])
  { /* invalid free (b was iterated) */
  free(a); free(b); }
  else
  { free(a); free(b); } /* ditto */

  return 0;
}
```

960521 – 1_false-valid-free.c

SV-COMP 2014: 55.6% of the tools in the *MemorySafety* category **are not able to find** the property violation

Step 1: Identification of safety properties

```
$ esbmc --64 --no-library --show-claims
960521-1_false-valid-free.c
file 960521-1_false-valid-free.c: Parsing
Converting
Type-checking 960521-1_false-valid-free
Generating GOTO Program
Pointer Analysis
Adding Pointer Checks
Claim 1:
file 960521-1_false-valid-free.c line 12 function foo
dereference failure: dynamic object lower bound
!(POINTER_OFFSET(a) + i < 0) || !(IS_DYNAMIC_OBJECT(a))
```

Step 1: Identification of safety properties

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!(POINTER_OFFSET(a) + i < 0) || !(IS_DYNAMIC_OBJECT(a))
```

Claims generated automatically by ESBMC do not necessarily correspond to errors

Step 2: Extract information from safety properties

Claims	Comments	Line	Property
Claim 1	dereference failure: dynamic object lower bound	12	!(POINTER_OFFSET(a) + i < 0) || !(IS_DYNAMIC_OBJECT(a))
Claim 2	dereference failure: dynamic object upper bound	12	!(POINTER_OFFSET(a) + i >= DYNAMIC_SIZE(a)) || !(IS_DYNAMIC_OBJECT(a))
Claim 3	dereference failure: dynamic object lower bound	14	!(POINTER_OFFSET(b) + i < 0) || !(IS_DYNAMIC_OBJECT(b))
Claim 4	File sum_array line 14 function main array `a' upper bound	14	!(POINTER_OFFSET(b) + i >= DYNAMIC_SIZE(b)) || !(IS_DYNAMIC_OBJECT(b))
...	...	...	...

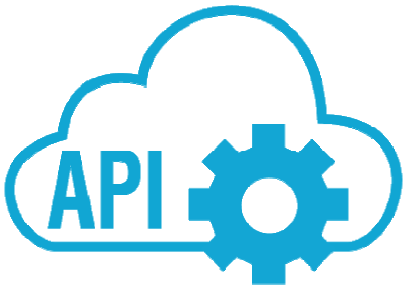
Step 3: Translation of safety properties

Translate claims provided by ESBMC to assertions into the C program:

- ✓ **INVALID-POINTER.**

$$INVALID - POINTER(i + pat) \ \boldsymbol{to}$$

IS _VALID_POINTER_MF (*LIST_LOG*, (*void∗*)&(*i+pat*), (*void∗*)(*intptr_t*)(*i+pat*))



#include <map2check.h>

Map2Check provides a library to the C program, which offers support to execute the functions generated by the translator.

Step 4: Memory tracking

Consists of two phases:

1) **identify and track variables** in the analyzed source code, as well as, the variable operations and assignments

2) **instrument the source code** with specific functions for **monitoring the memory addresses** and the addresses pointing by these variables according to the program execution

Step 4: Memory tracking

```
int *a, *b;
int n;

#define BLOCK_SIZE 128

void foo (){ ...

int main ()
{
  n = BLOCK_SIZE;
  a = malloc (n * sizeof(*a));
  b = malloc (n * sizeof(*b));
  *b++ = 0;
  foo ();
```

Phase 1: identify and track variables

Input: Abstract Syntax Tree (AST)
Output: Variables Tracking (Map)

Analyzing the program scope

foreach *node IN the AST* **do**
  if *type(node) == FuncDef* **then**
    compound_func = get the sub tree from node
    foreach *subNo FROM compound_func == Decl* **do** getDataFromVar(*subNo, 0*) ;
  end
  else if *type(node) == Decl* **then** getDataFromVar(*node, 1*) ;
end
Function getDataFromVar(*node, enableGlobalSearch*)

Step 4: Memory tracking

```
int *a, *b;
int n;

#define BLOCK_SIZE 128

void foo (){ ... }

int main ()
{
  n = BLOCK_SIZE;
  a = malloc (n * sizeof(*a));
  b = malloc (n * sizeof(*b));
  *b++ = 0;
  foo ();
  if (b[-1])
  { /* invalid free (b was iterated) */
  free(a); free(b); }
  else
  { free(a); free(b); } /* ditto */

  return 0;
}
```

Tracking of the variables

Pointer variable assignments

Step 4: Memory tracking

Phase 2: Instrumentation of the source code

- ✓ **mark_map_MF**. This function trackes the memory addresses (**`LIST_LOG`**) of the variables according to the program execution;
- ✓ **IS_VALID_DYN_OBJ_MF**. This function identifies if a dynamic object is valid;
- ✓ **INVALID_FREE**. This function identifies whether a given dynamic object can be released/deallocated from the memory properly;
- ✓ **CHECK_MEMORY_LEAK**. Identifies if, in the end of the program, some allocated memory is not released.

Step 4: Memory tracking

Tracking memory execution

```
3.  int *a, *b;
4.  int n;
5.
6.  #define BLOCK_SIZE 128
7.
8.  void foo
16.
17. int
18. {
19.   n
20.   a
21.   b
22.   *
23.   f
24.   if (  [-1])
25.   {
26.   f
27.   else
28.   { free(a); free(b); } /* ditto */
29.
30.   return 0;
31. }
```

Invalid free

Line	Address	Points to	Escope	Is Dynamic	Is Free
28	0x601050	0xb44034	global	0	1
28	0x601060	0xb44010	global	0	1
...	...	...	...	...	...
10	0x7fff39f18a2c	(nil)	foo	0	0
22	0x601050	0xb44034	global	0	0
21	0x601050	0xb44030	global	1	0
...	...	...	...	...	...

variable b was iterated

Step 5: Code instrumentation with assertions

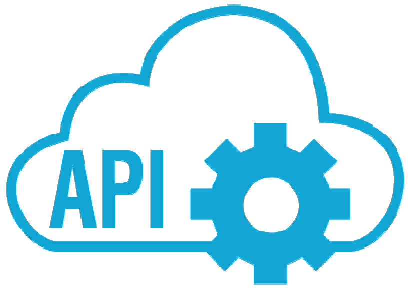
```
...

int main ()
{
  n = BLOCK_SIZE;
  a = malloc (n * sizeof(*a));
  b = malloc (n * sizeof(*b));
  *b++ = 0;
  foo ();
  if (b[-1])
  {
   ...
  }
  else
  {
    ASSERT(INVALID_FREE(LIST_LOG, (void *)(intptr_t)(a), 28));
    free(a);
ASSERT(INVALID_FREE(LIST_LOG, (void *)(intptr_t)(b), 28));
free(b);
  }
  return 0;
}
```

Step 6: Implementation of the tests

Model using C assertions

debugging



#include <map2check.h>

Model for CUnit

options/statements for unit testing

Unit Testing Framework

Step 6: Implementation of the tests

- #includes for CUnit
- #includes for Map2Check library
- #includes from analyzed C code
- The setup CUnit functions
- - Functions
  - - Test cases
  - - Global variables
  - - main = testClaims
- - New function main for Cunit
  - - It calls the setup to CUnit

```c
#include "CUnit/Basic.h"
#include "check_memory_safety_Map2Check.h"
#include <stdlib.h>
int init_suite1(void){...}
int clean_suite1(void){...}
int *a, *b;
int n;

#define BLOCK_SIZE 128

void foo ()
{ ... }

int testClaims ()
{
  ...
  foo ();
  if (b[-1])
  { /* invalid free (b was iterated) */
  free(a); free(b); }
  else
  { free(a); free(b); } /* ditto */

  return 0;
}

int main(){
  CU_pSuite pSuite = NULL;
  pSuite = CU_add_suite("check_code", init_suite1, clean_suite1);
  if(NULL==pSuite){...}
  if(CUE_SUCCESS != CU_initialize_registry()) return CU_get_error();
  if(NULL==CU_add_test(pSuite, "testClaims", testClaims))){...}
  CU_basic_set_mode(CU_BRM_VERBOSE);
  CU_basic_run_tests(); CU_cleanup_resgistry();
  return CU_get_error();
}
```

Step 7: Execution of the tests

```
VIOLATED PROPERTY
  Type     : Invalid FREE
  Location: In the line {28}
  Last Use: In the line {22}

FAILED
    1. mf_960521-1_false-valid-free.c:108
INVALID_FREE(LIST_LOG, (void *)(intptr_t)b,28)

Run Summary:     Type  Total    Ran Passed Failed Inactive
               suites      1      1    n/a      0        0
                tests      1      1      0      1        0
              asserts    516    516    515      1      n/a

Elapsed time =    1.880 seconds
```

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Planning and Designing the Experiments

Goal: Analyzing the ability of Map2Check to **generate and verify** test cases related to **memory management.**

- ✓ The experiments are conducted on an Intel Core i7-2670QMCPU, 2.20GHz, 32GB RAM com Linux OS
- ✓ The time limit to the verification is 15 min

Disponível em https://github.com/hbgit/Map2Check

Planning and Designing the Experiments

- ✓ We consider 61 ANSI-C programs from the *MemorySafety* category of the SV-COMP'14 benchmark

- ✓ Comparison to the tools:
  - Valgrind's Memcheck (Nethercote e Seward, 2007)
  - CBMC (Clarke et al., 2004)
  - LLBMC (Merz et al., 2012)
  - CPAChecker (Beyer e Keremoglu, 2011)
  - Predator (Dudka et al., 2014)
  - ESBMC (Cordeiro et al., 2012).

Experiment's Execution and Results Analysis

> 76%

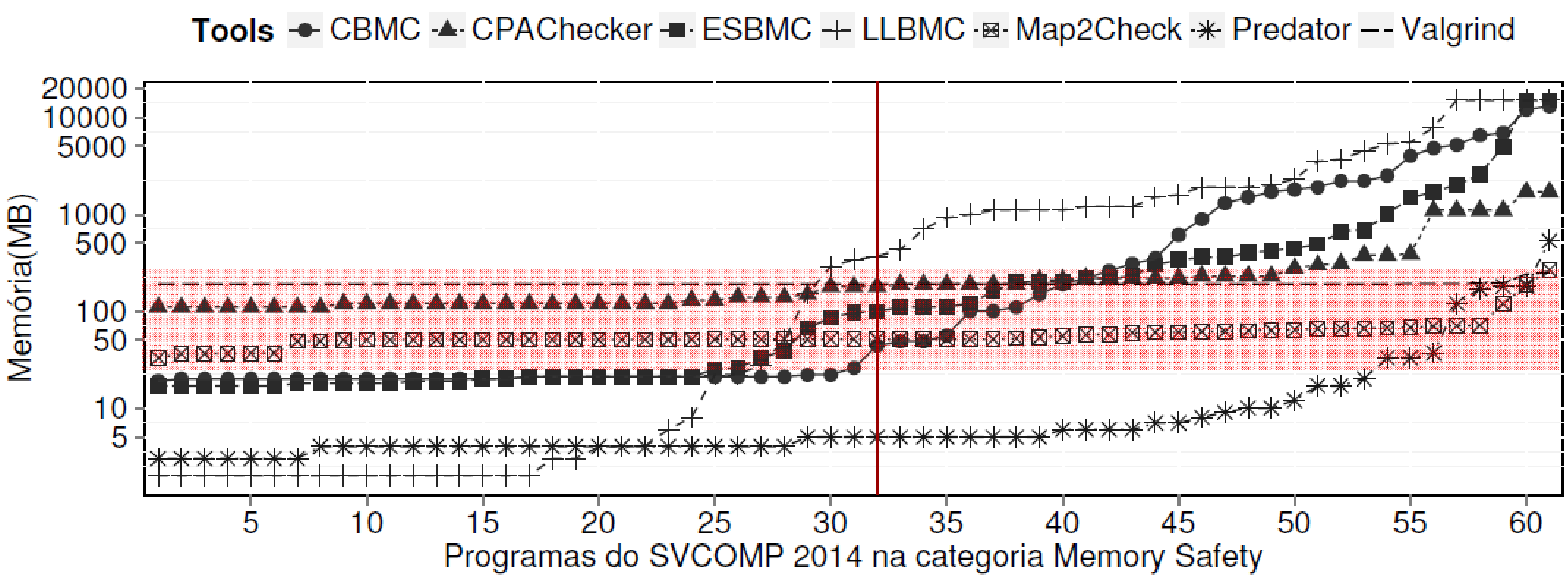
95.72% 95.08% 93.44%

Tool	CPAChecker	Map2Check	Valgrind	CBMC	Predator	LLBMC	ESBMC
Correct Results	59	58	57	46	43	31	7
False Negatives	0	0	0	8	0	0	0
False Positives	0	0	0	2	12	0	36
Unknown and TO	2	3	4	5	6	30	18
Time (min)	23.33	190.98	151.57	200	76.66	416.66	139.06

Experiment's Execution and Results Analysis

Memory consumed by the tools in the programs

- ✓ Map2Check is the **2nd tool** that consumes less memory
- ✓ Map2Check in **95%** of the programs has consumed about 50 MB



Experiment's Execution and Results Analysis

The runtime verification:

- ✓ Map2Check is **54.16%** faster than LLBMC and **4.5%** than CBMC

- ✓ Map2Check does not identify more correct results only, but also generates less Unknown and TO than CPAChecker

- ✓ Map2Check time: the concrete execution of the nondeterministic programs
  - The function `__VERIFIER_nondet_int()` in loop structures
  - Map2Check depends on a **random function** to determine the **halting condition of a loop**

Experiment's Execution and Results Analysis

Analyzing Map2Check in the context of the SVCOMP'14 in the *MemorySafety* category.

The scores could be ranked with negative points

Scores:

1st place: CPAChecker = 95 e Map2Check = 95

2th place: LLBMC = 38

3th place: Predator = 14

Experiment's Execution and Results Analysis

We had participated in **SV-COMP 2015** with **Map2Check tool** in the *MemorySafety* category

- ✓ Updates in SV-COMP:
  - In SV-COMP 2014 the total file **was 61** and in SV-COMP 2015 **was 205**
  - ✓ The scores were updated to penalize incorrect results

- ✓ Map2Check **won the 6th** from 9 tools (number of correct programs **was 165 from 205**)
  - Forester (Holik et al., 2015)
  - Seahorn (Kahsai et al., 2015)
  - CBMC (Clarke et al., 2004a)

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Conclusions and Future Work

- ✓ We presented a method to:
  - **integrate unit testing with model checkers**, focusing on memory management defects
  - disseminate the application of formal methods and **helping developers not very familiar** with this subject to verify large C programs
- ✓ Map2Check can be adopted as a **complementary technique** for the verification performed by **BMC tools**
  - Mainly when BMC tools cannot, usually **because of time-out**; or when there are **false negative or false positive**

Conclusions and Future Work

- ✓ The experimental results have shown to be very effective
- ✓ The Map2Check method has detected at least as many memory management defects as the state-of-the-art tools

For future work

- ✓ To improve the verification runtime and precision of Map2Check:
  - adopting program invariants
  - static verification based on abstract domain
- ✓ Adopting a witness checker

Questions ?

Thank you for your attention!

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