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SMT-Based Bounded Model Checking for Embedded ANSI-C Software

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Software Model Checking – State of The Art in 2009

Software model checking had made **significant progress** but faced challenges of scalability, concurrency, and integration into the software development process

1. **Tools**: Verifiers were available (***BLAST***, ***CBMC***, ***JPF***, ***NuSMV***, and ***Spin***), but had **limitations** regarding **scalability, modeling languages**, **types of properties**.
2. **SAT/SMT solvers**: Few verifiers could support SAT (***CBMC***, ***SLAM***) or even SMT solvers (***SMT-CBMC***). **The viability of using SMT solvers was unclear**.
3. **Concurrency**: Researchers were developing techniques to model and verify multi-threaded programs more effectively (**ongoing challenge**).
4. **Integration with Development Process**: Growing emphasis on integrating model checking into the software development process.
5. **Hybrid Approaches**: Combine model-checking with other techniques, such as testing and static analysis, to improve verification accuracy and efficiency.

Objective of this work

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Exploit SMT to improve BMC of embedded software

- exploit background theories of SMT solvers
- provide suitable encodings for
  - pointers
  - bit operations
  - unions
  - arithmetic over- and underflow
- build an SMT-based BMC tool for full ANSI-C
  - build on top of CBMC front-end
  - use several third-party SMT solvers as back-ends
- evaluate ESBMC over embedded software applications

SAT-based CBMC [D. Kroening]

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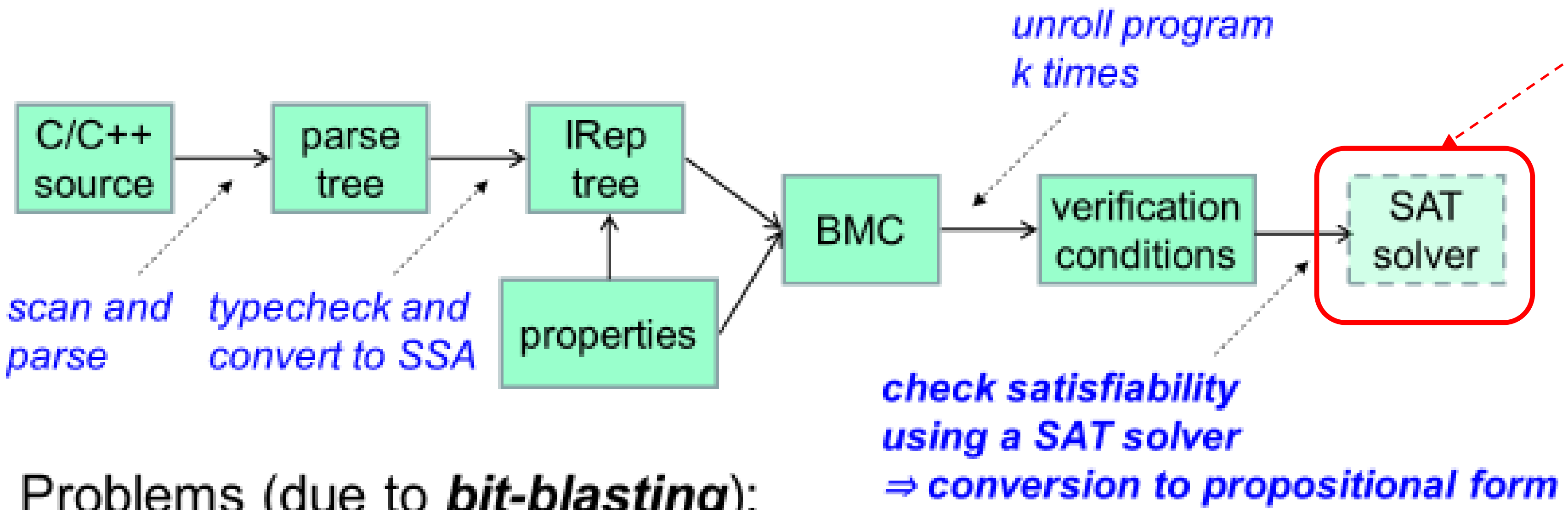
implements BMC for ANSI-C/C++ programs using SAT-solvers:



replace by SMT translation and solver

Problems (due to ***bit-blasting***):

- **complex expressions** lead to large propositional formulae
- **high-level information is lost**

Encoding of x == a + b

- *represent x, a, b by n independent propositional variables each*
- *represent addition by logical circuit*
- *represent equality by equivalences on propositional variables*

Encoding of Numeric Types

- SMT solvers typically provide different encodings for numbers:
  - abstract domains ($\mathbb{Z}$, $\mathbb{R}$)
  - fixed-width bit vectors (`unsigned int`, …)
    - ▹ "internalized bit-blasting"
- verification results can depend on encodings

$$(a > 0) \wedge (b > 0) \Rightarrow (a + b > 0)$$

valid in abstract domains such as $\mathbb{Z}$ or $\mathbb{R}$

doesn't hold for bitvectors, due to possible overflows

  - majority of VCs solved faster if numeric types are modelled by abstract domains but possible loss of precision
  - ESBMC supports both encodings

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Encoding of Structured Datatypes

- arrays and records / tuples typically handled directly by SMT-solver
- pointers modelled as tuples
  - p.o ≙ representation of underlying object
  - p.i ≙ index (if pointer used as array base)

```
int main() {
  int a[2], i, x, *p;
  p=a;
  if (x==0)
    a[i]=0;
  else
    a[i+1]=1;
  assert(*(p+2)==1);
}
```

⇒ C

$p_1 := store(p_0, 0, \&a[0])$
$\wedge\ p_2 := store(p_1, 1, 0)$
$\wedge\ g_2 := (x_2 ==$
$\wedge\ a_1 := store(a_0, i_0$
$(a_2, 1+ i_0, 1)$
$\wedge\ a_4 := ite($ $_1, a_1, a_3)$
$\wedge\ p_3 := store(p_2, 1, select(p_2, 1)+2)$

Store object at position 0

Store index at position 1

Update index

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Encoding Numeric Types as Bitvectors

Bitvector encodings need to handle

- type casts and implicit conversions
  - arithmetic conversions implemented using word-level functions (part of the bitvector theory: extractBits, …)
    - ▹ different conversions for every pair of types
    - ▹ uses type information provided by front-end
  - conversion to / from bool via if-then-else operator
- arithmetic over- / underflow
  - standard requires modulo-arithmetic for unsigned integers
  - define error literals to detect over- / underflow for other types

$$res\_ok \Leftrightarrow \neg\, overflow(x, y) \wedge \neg\, underflow(x, y)$$

    - ▹ similar to conversions
- floating-point numbers
  - approximated by fixed-point numbers, integral part only
  - represented by fixed-width bitvector

Comparison to SAT-CBMC [D. Kroening]

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			SAT-CBMC				ESBMC			
			Time		#P		Time		#P	
Module	#L	#P	Enc.	**Solver**	Fail	Error	Enc.	**Solver**	Fail	Error
fft1	218	72	0.4	<0.1	0	0	0.4	<0.1	0	0
fft			MO	-	0	39	2337.8	<0.1	0	0
jf			1.2	<0.1	1	0	0.5	2.4	1	0
lr			MO	-	0	35	132.6	0.2	0	0
lu			4.5	TO	0	1	<0.1	1.44	0	0
q			18.8	TO	0	1	1.2	7.7	0	0
p			15.3	0.1	1	0	12.3	5.8	1	0
ad			71.3	3.5	0	0	45.7	9.2	0	0
laplace	110	76	30.8	TO	0	76	12.3	0.3	0	0
exStbKey	558	18	1.2	<0.1	0	0	1.2	<0.1	0	0
exStbHDMI	1045	25	167.9	78.9	0	0	164.4	33.5	0	0
exStbLED	430	6	195.9	130.0	0	0	165.6	44.5	0	0
exStbHwAcc	1432	113	0.7	<0.1	0	0	0.7	<0.1	0	0
exStbRes	353	40	271.8	319.0	0	0	269.3	1161.0	0	0

SMT-solver often significantly faster than SAT-solver

Comparison to SMT-CBMC [A. Armando et al.]

- SMT-based BMC for C, built on top of CVC3 (hard-coded)
  - limited coverage of language
- Goal: compare efficiency of encodings

Module	ESBMC		SMT-CBMC
	Z3	**CVC3**	**CVC3**
BubbleSort (n=35)	[illegible]	**28.7**	**94.5**
[illegible]	[illegible]	MO	*
[illegible]	[illegible]	**8.5**	**66.5**
[illegible]	[illegible]	MO	MO
BellmanFord	0.3	**0.5**	**13.6**
Prim	0.5	**16.9**	**18.4**
StrCmp	38.8	**9.9**	**TO**
SumArray	4.7	**1.2**	**113.8**
MinMax	6.2	MO	MO

ESBMC substantially faster, even with identical solvers
⇒ probably better encoding

Conclusions

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- SMT-based BMC is more efficient than SAT-based BMC
  - but not uniformly
- described and evaluated first SMT-based BMC for ANSI-C
  - provided encodings for typical ANSI-C constructs not directly supported by SMT-solvers
- available at `users.ecs.soton.ac.uk/lcc08r/esbmc/`

Future work:

- better handling of floating-point numbers
- concurrency (based on Pthread library)
- termination analysis

ESBMC – Post 2009: Building a better tool

- SMT-Based Bounded Model Checking for Embedded ANSI-C Software. [TSE 2012, 371 citations]
- ESBMC 5.0: an industrial-strength C model checker. [ASE 2018, 95 citations]
- Verifying Multi-Threaded Software using SMT-Based Context-Bounded Model Checking. [ICSE 2011, 202 citations]
- Context-Bounded Model Checking with ESBMC 1.17. [TACAS 2012, 69 citations]
- Model Checking LTL Properties over ANSI-C Programs with Bounded Traces. [Softw. Syst. Model. 2015, 38 citations]
- Handling Unbounded Loops with ESBMC 1.20. [TACAS 2013, 55 citations]
- ESBMC v6.0: Verifying C Programs Using k-Induction and Invariant Inference - (Competition Contribution). [TACAS 2019, 58 citations]

ESBMC – Post 2009: Building a *software engineering* tool

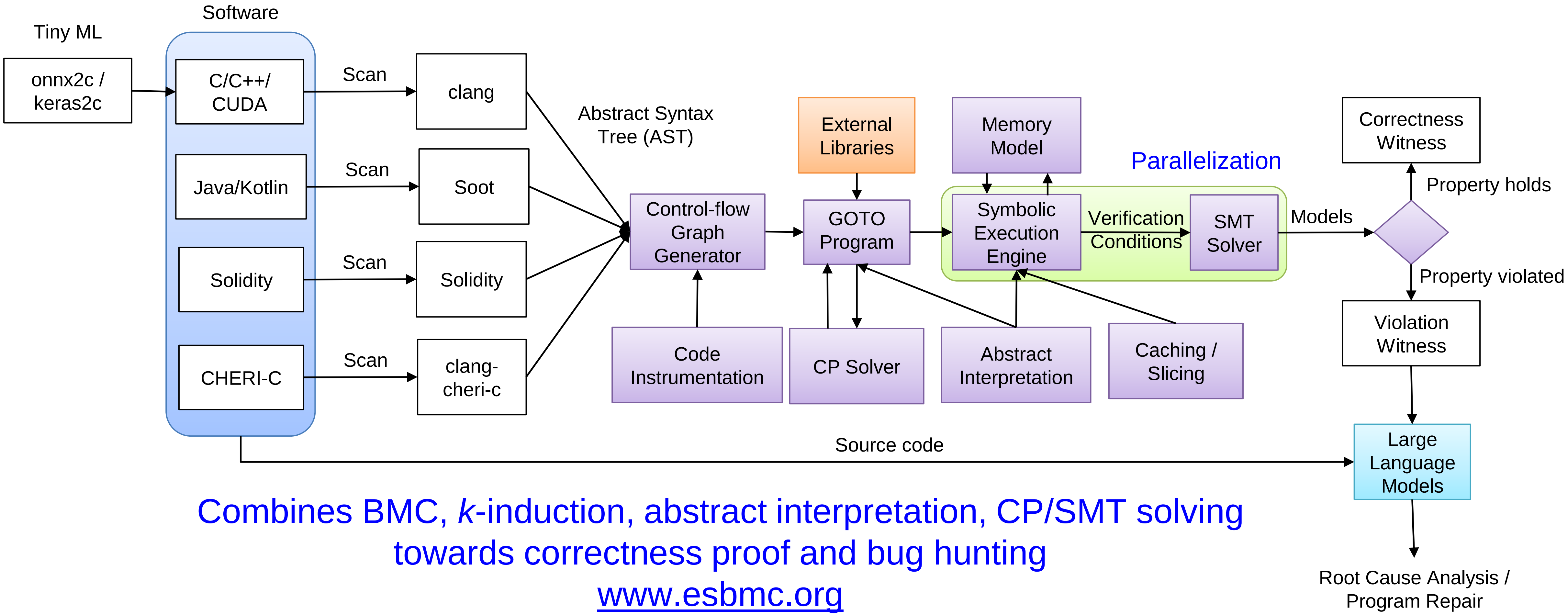
- Continuous Verification of Large Embedded Software Using SMT-Based Bounded Model Checking. [ECBS 2010, 19 citations]
- ESBMC: Scalable and Precise Test Generation based on the Floating-Point Theory. [FASE 2020, 13 citations]
- ESBMC 6.1: Automated Test Case Generation Using Bounded Model Checking. [STTT 2021, 13 citations]
- A Method to Localize Faults in Concurrent C Programs. [JSS 2017, 16 citations]
- A New Era in Software Security: Towards Self-Healing Software via Large Language Models and Formal Verification. [Under Review ACM TOSEM 2023, 5 citations]
- The FormAI Dataset: Generative AI in Software Security Through the Lens of Formal Verification. [PROMISE 2023]

ESBMC – Post 2009: Supporting more languages

- SMT-Based Bounded Model Checking of C++ Programs [ECBS 2013, 49 citations]
- Bounded Model Checking of C++ Programs Based on the Qt Cross-Platform Framework. [STVR 2017, 21 citations]
- Verifying CUDA Programs using SMT-Based Context-Bounded Model Checking. [SAC 2016, 30 citations]
- ESBMC-Jimple: Verifying Kotlin Programs via Jimple Intermediate Representation. [ISSTA 2022]
- ESBMC-Solidity: An SMT-Based Model Checker for Solidity Smart Contracts. [ICSE 2022, 3 citations]
- ESBMC-CHERI: Towards Verification of C Programs for CHERI Platforms with ESBMC. [ISSTA 2022, 2 citations]

ESBMC today: integrated logic-based verification platform

Logic-based automated reasoning for checking the **safety** and **security** of **AI and software systems**



Combines BMC, *k*-induction, abstract interpretation, CP/SMT solving towards correctness proof and bug hunting

www.esbmc.org

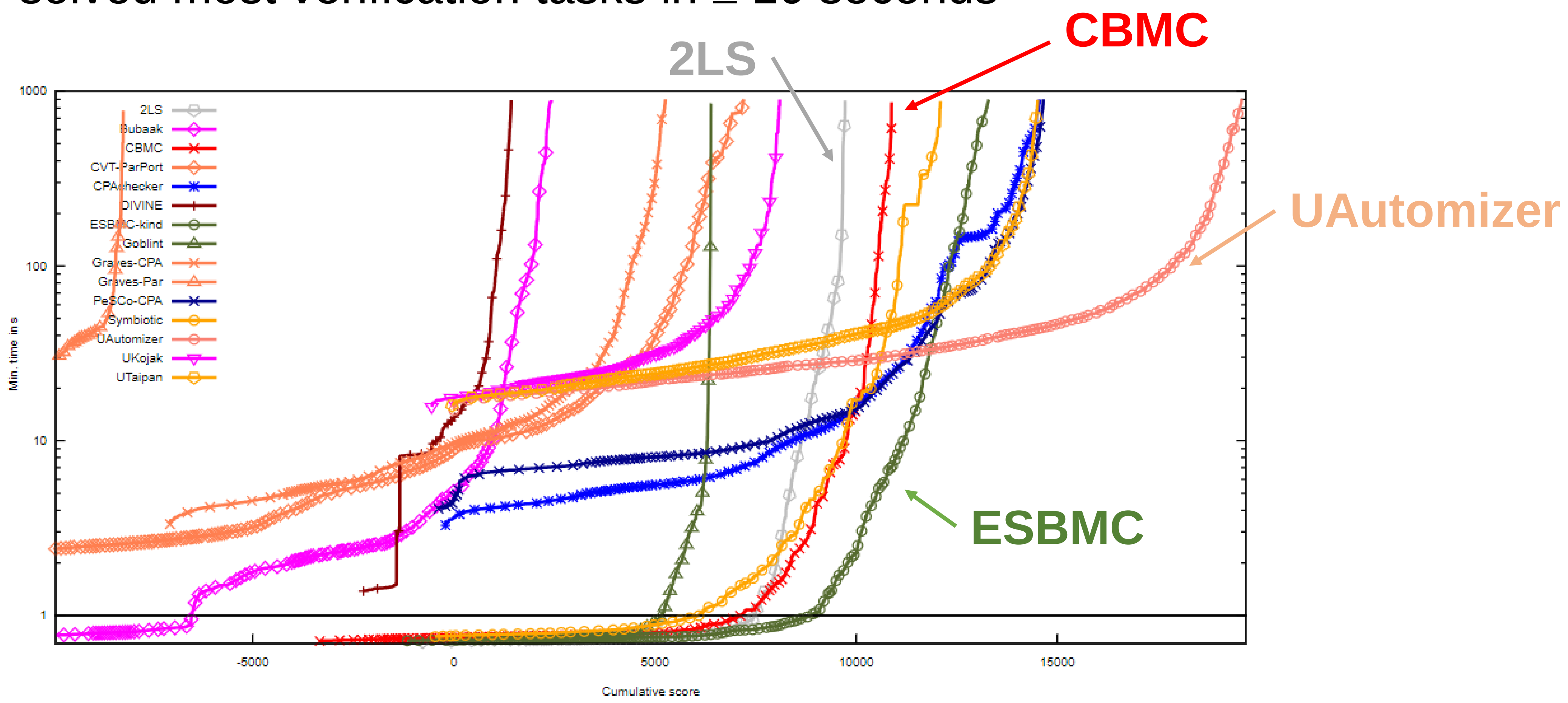
International Competitions

- Intl. Competition on Software Verification (TACAS 2012-2023)
  - 6 x Gold 🥇
  - 4 x Silver 🥈
  - 10 x Bronze 🥉
- Intl. Competition on Software Testing (FASE 2020-2023)
  - 7 x Gold 🥇
  - 1 x Silver 🥈
  - 1 x Bronze 🥉

13 x gold, 5 x silver and 11 bronze (29 medals)

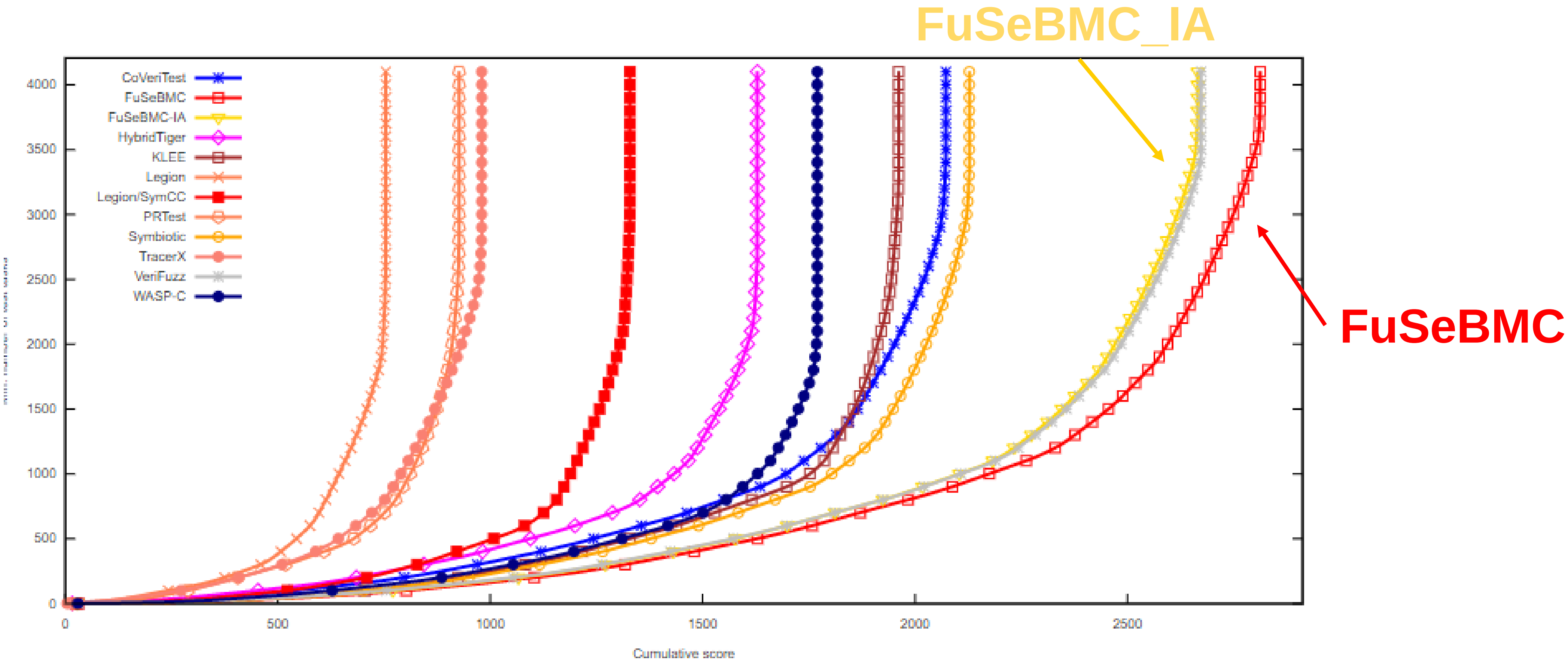
Intl. Software Verification Competitions (SV-Comp 2023)

- SV-COMP 2023, 23805 verification tasks, max. score: 38644
- ESBMC solved most verification tasks in ≤ 10 seconds



Verification of the `Overall` Category

Intl. Software Testing Competitions (Test-Comp 2023)



FuSeBMC achieved 3 awards: 1st place in `Cover-Error`, 1st place in `Cover-Branches`, and 1st place in `Overall`

Alshmrany, K., Aldughaim, M., Bhayat, A., Cordeiro, L.: FuSeBMC v4: Smart Seed Generation for Hybrid Fuzzing - (Competition Contribution). FASE 2022: 336-340

https://test-comp.sosy-lab.org/2023/

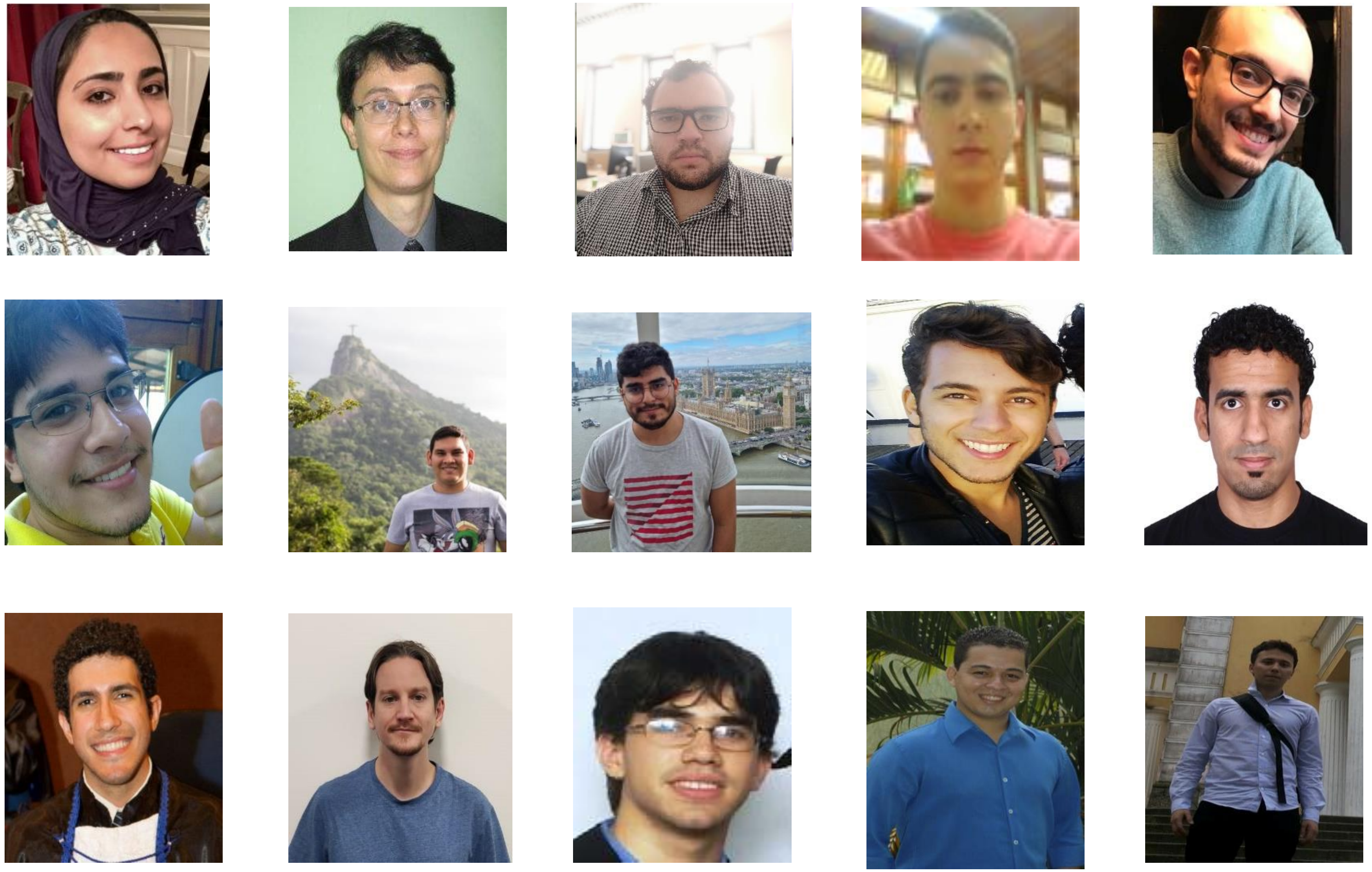
Impact: Awards and Industrial Deployment

- **Distinguished Paper Award** at ICSE’11
- **Best Paper Award** at SBESC’15
- **Most Influential Paper Award** at ASE’23
- **29 awards** from the international competitions on software verification (SV-COMP) and testing (Test-Comp) 2012-2023 at **TACAS/FASE**
  - Bug Finding and Code Coverage
- **Intel** deploys **ESBMC** in production as one of its verification engines for **verifying firmware in C**
- **Nokia and ARM** have found **security vulnerabilities** in **C/C++ software**
- **Funded by government** (EPSRC, British Council, Royal Society, CAPES, CNPq, FAPEAM) and **industry** (Intel, Motorola, Samsung, Nokia, ARM)

(Real) Impact: Students and Contributors

- 5 PhD theses
- 30+ MSc dissertations
- 30+ final-year projects

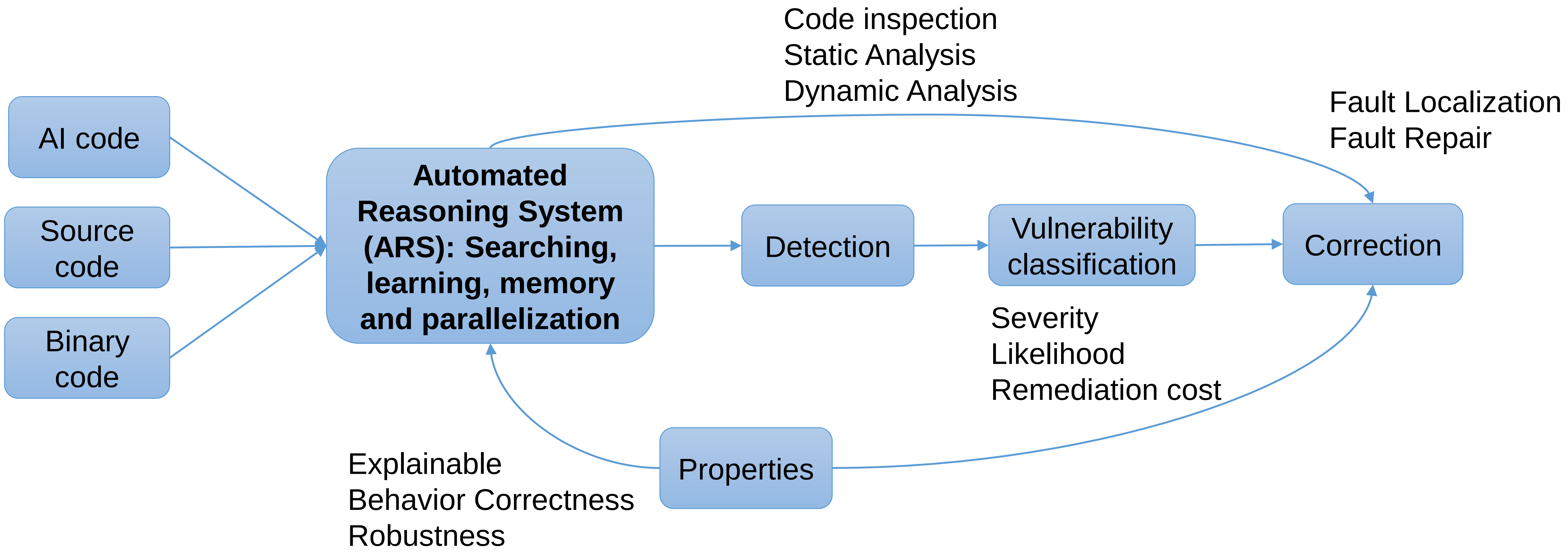
- GitHub:
  - 35 contributors
  - 21,580 commits
  - 195 stars
  - 81 forks



https://github.com/esbmc/esbmc

Vision: Automated Reasoning System for Secure SW and AI

Develop an automated reasoning system for safeguarding software and AI systems against security vulnerabilities in an increasingly digital and interconnected world



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