An Overview of Automated Program Analysis

Raphaël Monat – SyCoMoRES team

`rmonat.fr`

CRIStAL’s CyberSecurity Seminar
21 Oct. 2024

Introduction

whoami

Research Scientist at Inria since Sep. 2022.

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Research Interests

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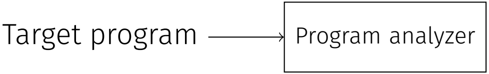
Target program

Automated Program Analysis



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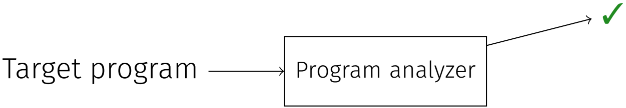

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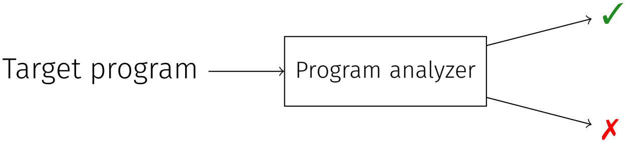

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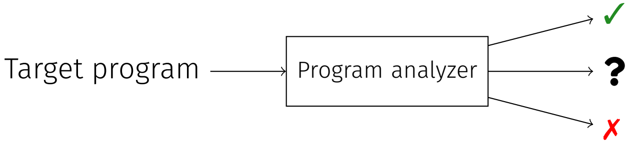

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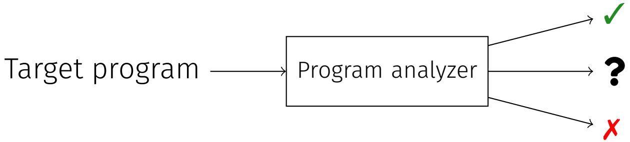

Motivation

Sheer quantity of programs and changes during their life:

Manual processes (e.g. testing, manual verification) will not scale!

A Program Analysis Recipe

Target property φ

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- Absence of runtime errors

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Requirement: <u>semantics of the program representation</u>

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$\Longrightarrow$ now build $\texttt{Analyzer}_{\varphi}(\text{prog} : i)$

Turing & Rice to the Rescue (or not?)

Sound	All errors in program reported by analyzer

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All errors reported by analyzer are replicable in program	Complete	Sound	All errors in program reported by analyzer

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Guaranteed Termination

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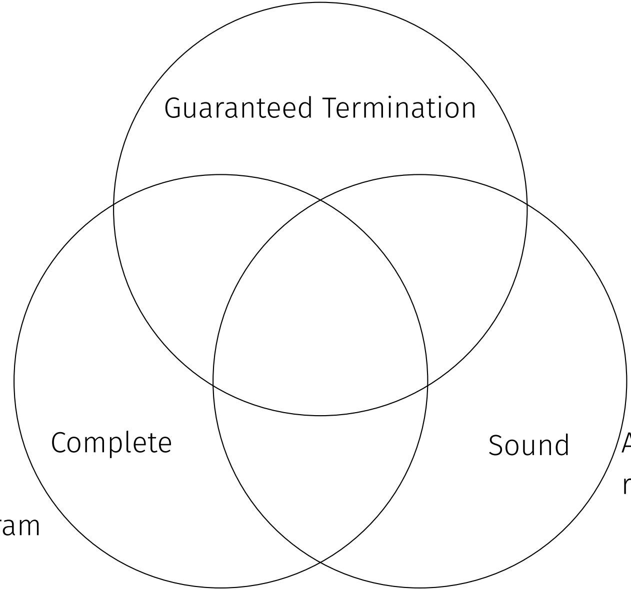

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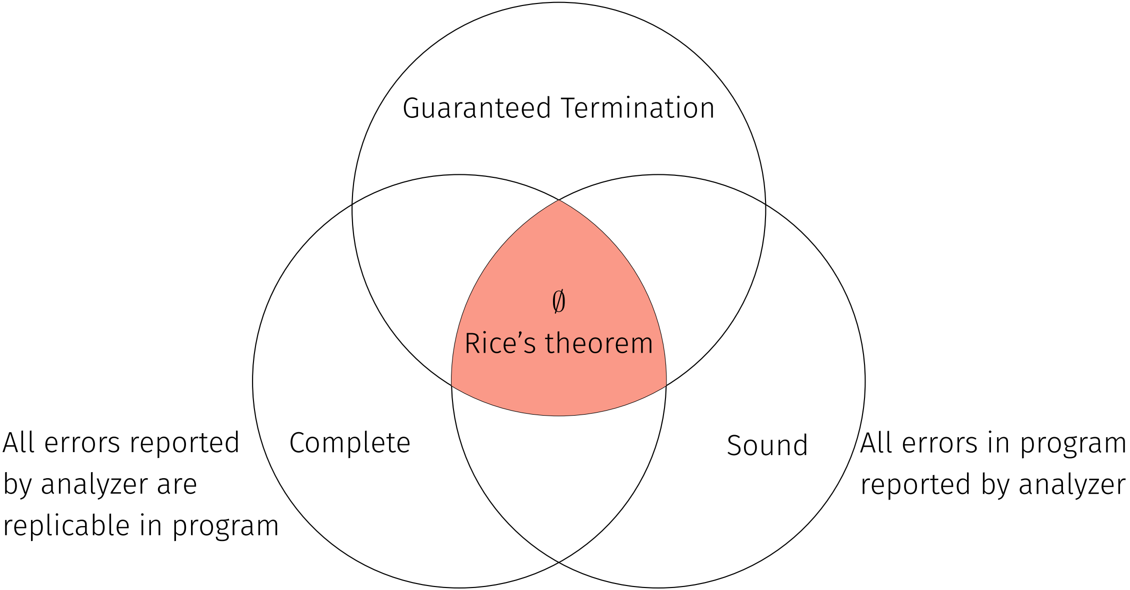

Outline

Overview of Program Analysis Techniques

Symbolic Execution

Core idea: systematic generation of testcases

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Explore all program paths

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if x > 0:
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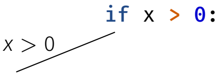

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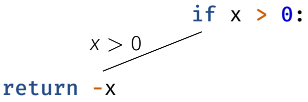

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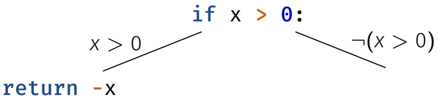

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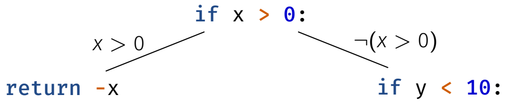

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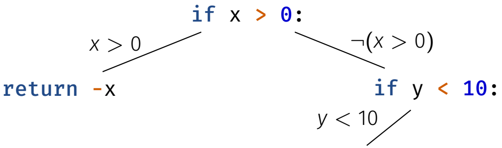

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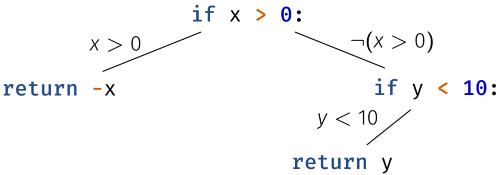

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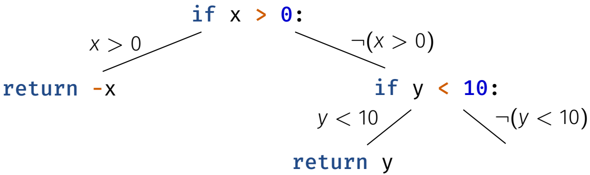

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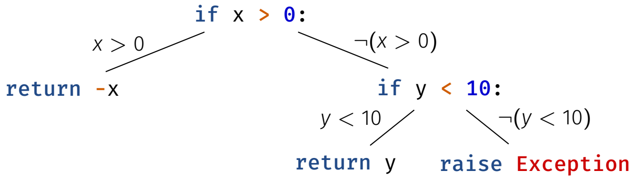

Symbolic Execution (II)

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Further references

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- Constraint solvers are currently SMT solvers: Z3 [MB08], CVC5 [Bar+22], Alt-Ergo [Con+18], SMT-LIB interface [BFT16]

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- White-box = symbolic execution

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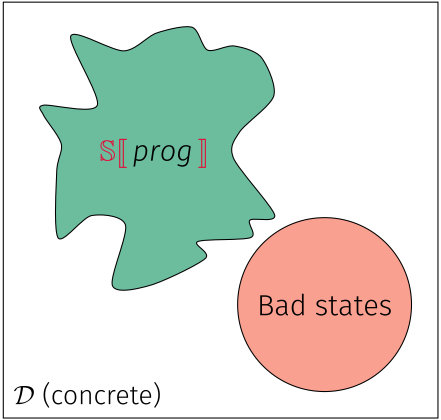
- Suggested entry-point: Miné [Min17]

Core Ideas behind Abstract Interpretation

Approximating a Complex World, with Guarantees



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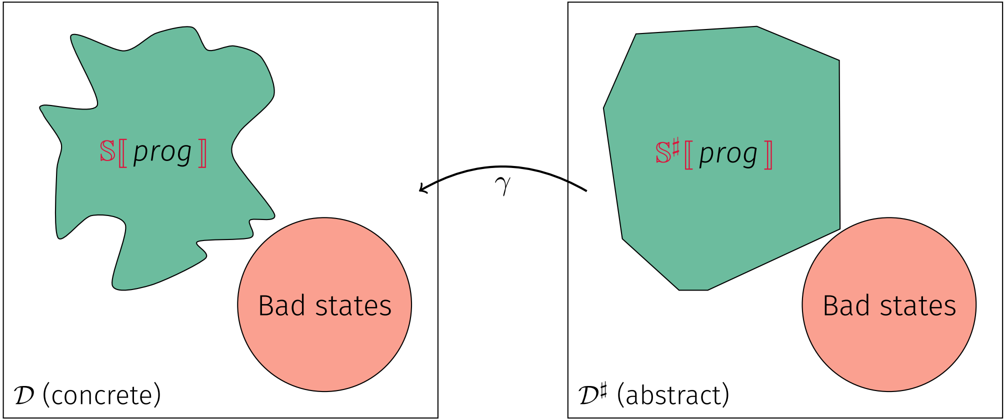

Interpret in non-standard domain

Program proved safe

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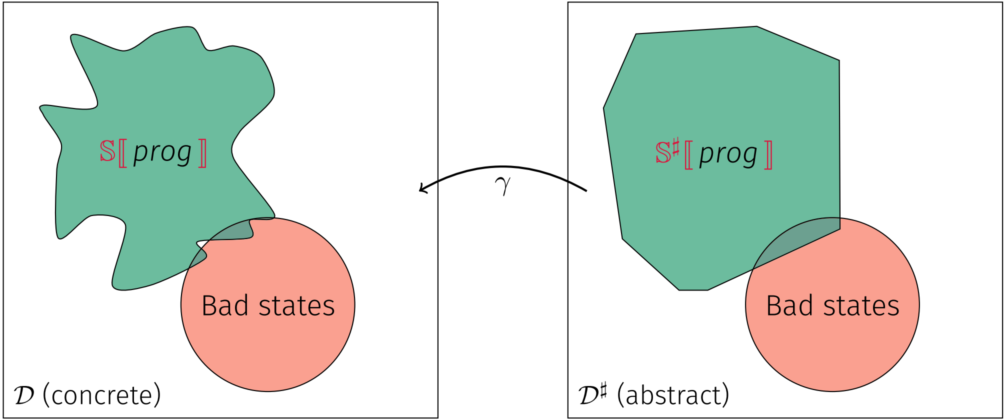

True alarm

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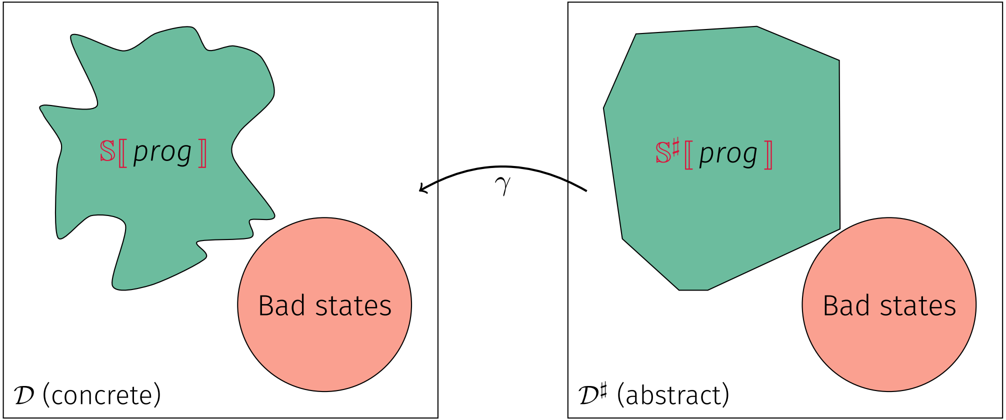

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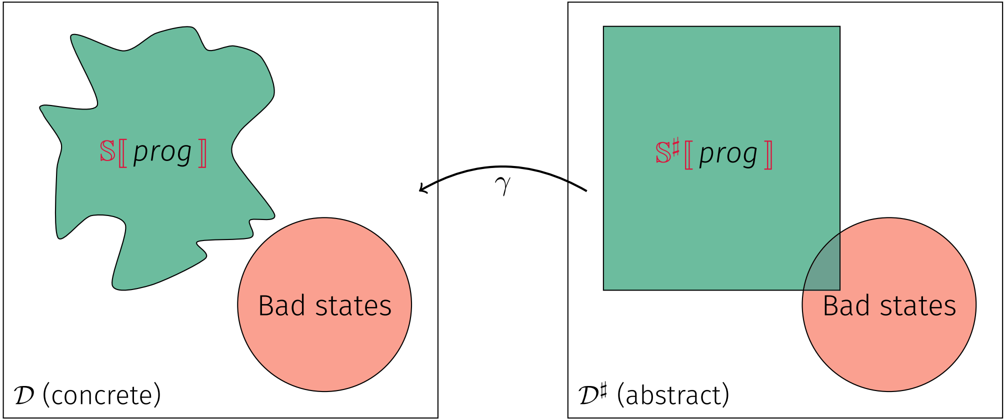
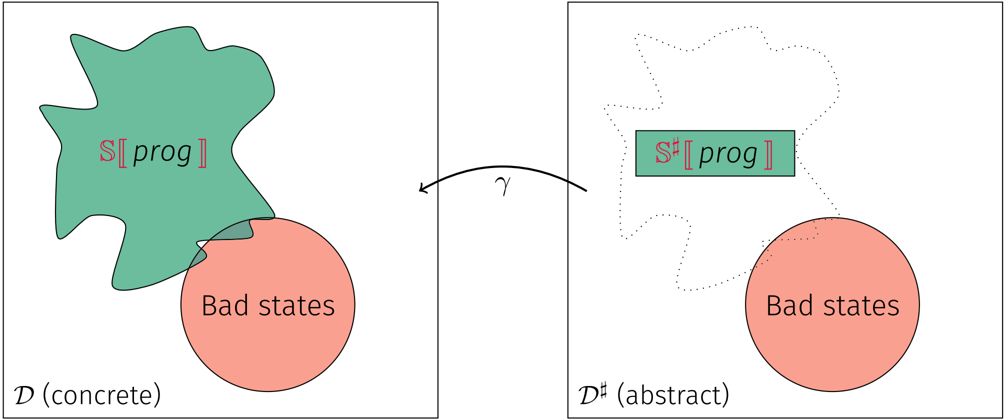


False alarm (Abstraction too coarse)

Approximating a Complex World, with Guarantees



Unsound analysis
(shouldn't happen)

Merging Everything to Scale

Merging States

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  - $\sigma^\sharp = x \mapsto [0, 2147483647]$

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Merging Paths

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Merging can also be applied to arrays, ...

Widening – Generalization Operator

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Iteration	Values of `i` in loop
0	[0, 0]
1	[0, 1]
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Widening – Generalization Operator

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Precision can be recovered through decreasing iterations

$\Longrightarrow$ $\mathtt{i} = [0, 99]$

A Modern Abstract Interpreter: Mopsa

Modular **O**pen **P**latform for **S**tatic **A**nalysis [Jou+19]

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  - High expressivity

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- Ease development of relational static analyses
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- Open-source (LGPL)
- Can be used as an experimentation platform

Contributors (2018–2024, chronological arrival order)

- A. Miné
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- M. Journault
- A. Fromherz
- D. Delmas
- R. Monat
- G. Bau
- F. Parolini
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Maintainers in bold.

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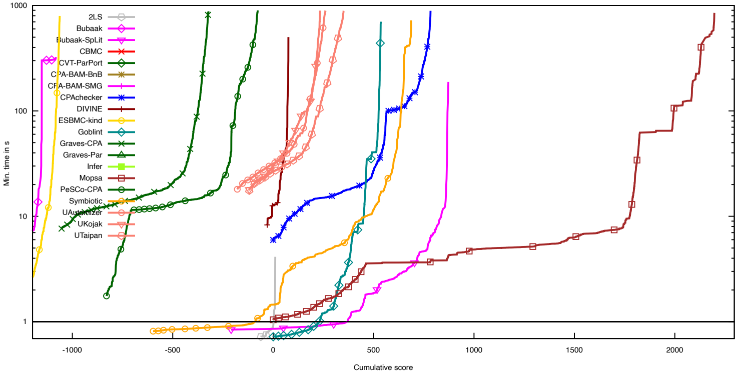

Multilanguage Analysis – Monat, Ouadjaout, and Miné [MOM21]

Assessment 20% of the 200 most popular Python libraries rely on C code

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Our approach: Combined analysis of C, Python and interface code

Library	C + Py. Loc	Tests	⏲/test	$\frac{\text{\# proved checks}}{\text{\# checks}}$ %	# checks
`noise`	1397	15/15	1.2s	99.7%	6690
`cdistance`	2345	28/28	4.1s	98.0%	13716
`llist`	4515	167/194	1.5s	98.8%	36255
`ahocorasick`	4877	46/92	1.2s	96.7%	6722
`levenshtein`	5798	17/17	5.3s	84.6%	4825
`bitarray`	5841	159/216	1.6s	94.9%	25566

Coreutils – Ouadjaout and Miné [OM20]

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Benchmark	Time	Selectivity	# checks
basename	33.79s	98.65%	11,731
dirname	21.68s	99.61%	11,307
echo	19.26s	99.43%	11,010
false	14.50s	99.72%	10,774
pwd	22.04s	99.62%	11,502
rmdir	39.00s	99.22%	11,699
sleep	23.79s	99.46%	11,546
tee	35.69s	98.76%	12,057
timeout	32.28s	98.51%	12,420
true	9.55s	99.72%	10,774
uname	20.61s	99.52%	11,943
users	20.82s	99.06%	11,668
whoami	13.03s	99.66%	11,329

Non-exploitability – Parolini and Miné [PM24]

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Test suite	Domain	Analyzer	Alarms	Time
Coreutils	Intervals	MOPSA	4,715	1:17:06
		MOPSA-NEXP	1,217 (-74.19%)	1:28:42 (+15.05%)
	Octagons	MOPSA	4,673	2:22:29
		MOPSA-NEXP	1,209 (-74.13%)	2:43:06 (+14.47%)
	Polyhedra	MOPSA	4,651	2:12:21
		MOPSA-NEXP	1,193 (-74.35%)	2:30:44 (+13.89%)
Juliet	Intervals	MOPSA	49,957	11:32:24
		MOPSA-NEXP	13,906 (-72.16%)	11:48:51 (+2.38%)
	Octagons	MOPSA	48,256	13:15:29
		MOPSA-NEXP	13,631 (-71.75%)	13:41:47 (+3.31%)
	Polyhedra	MOPSA	48,256	12:54:21
		MOPSA-NEXP	13,631 (-71.75%)	13:21:26 (+3.50%)

Future Work Around Mopsa

- Scalability (compositional function analyses)

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- Maintenance and development effort
- New languages, properties, specific programs

Conclusion

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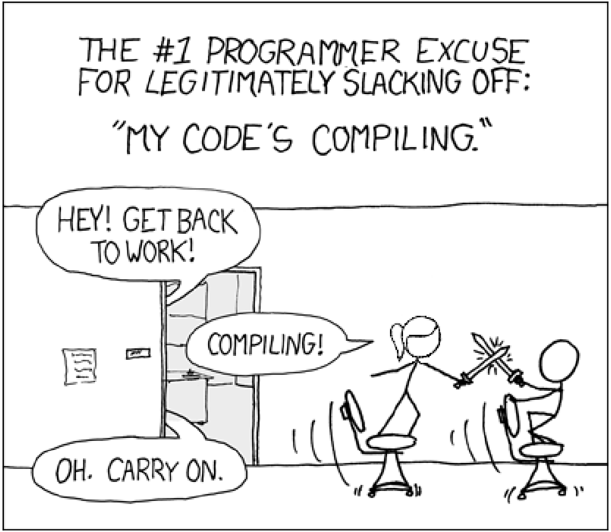
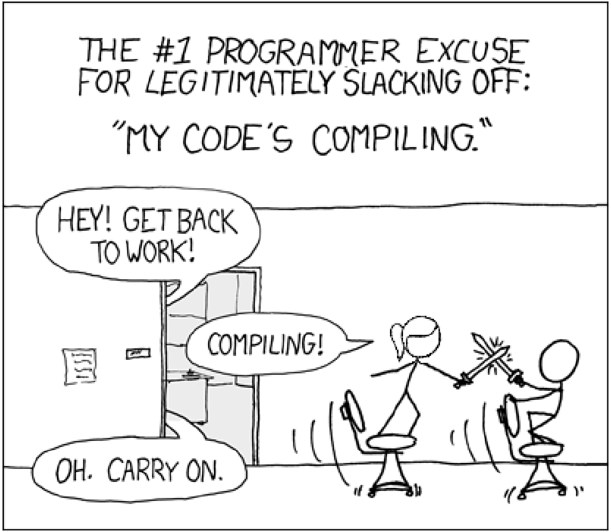


xkcd.com/303

Conclusion



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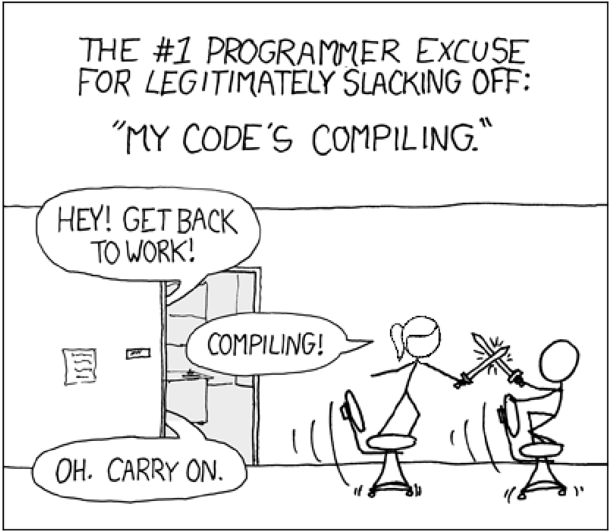
Techniques

- Symbolic execution

Conclusion



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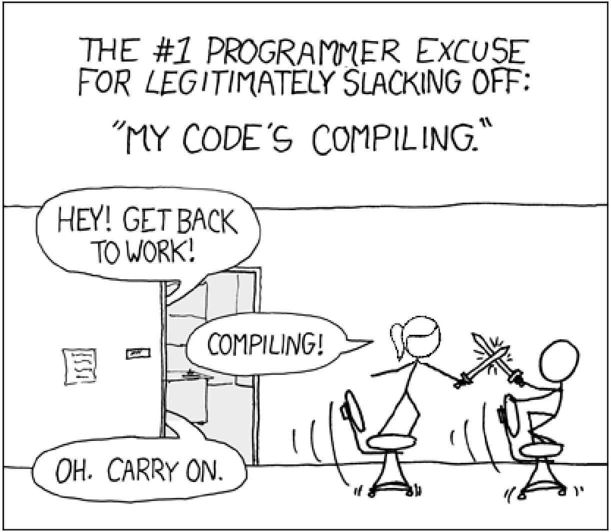

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Techniques

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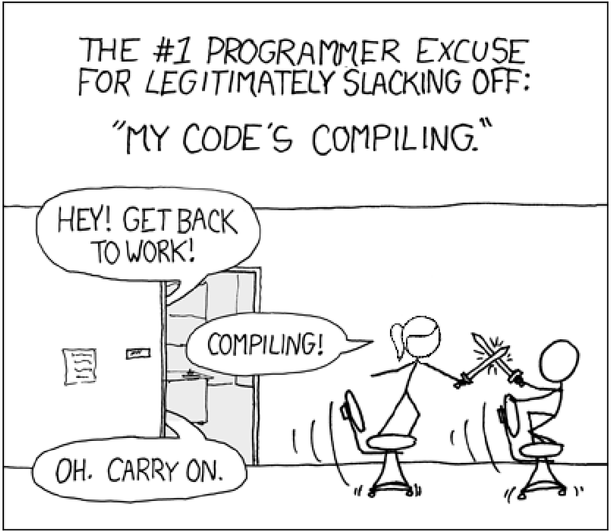

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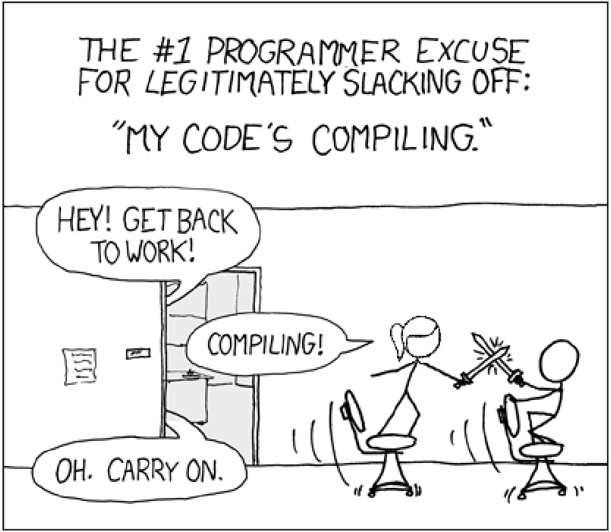

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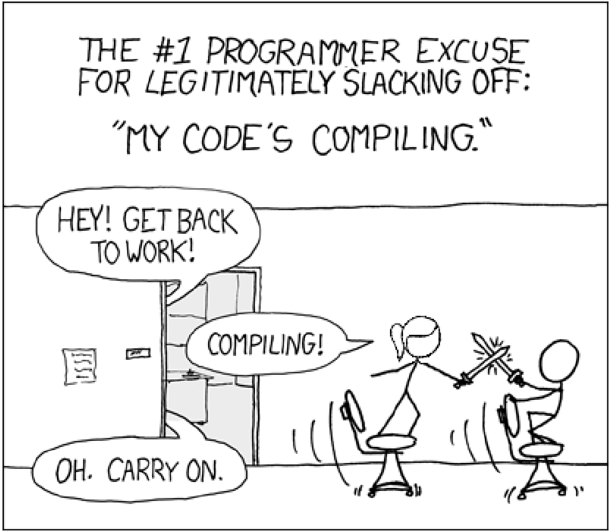

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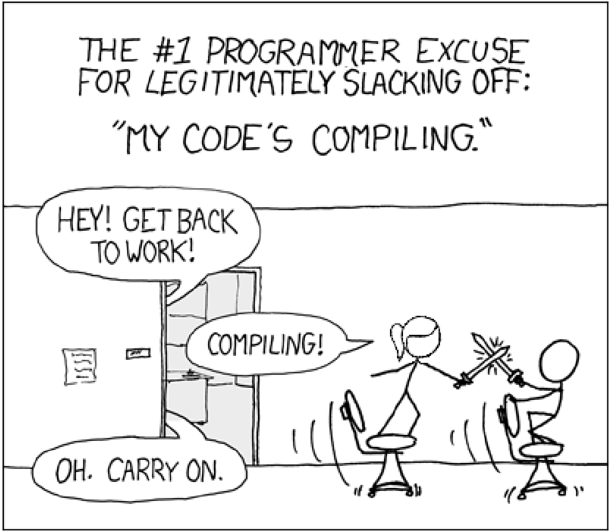

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- Symbolic execution
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- Benchmarks; usecases

References – I

[Bal+18] Roberto Baldoni et al. **"A Survey of Symbolic Execution Techniques".** In: ACM Comput. Surv. 3 (2018), 50:1–50:39.

[Bal+19] Clément Ballabriga et al. **"Static Analysis of Binary Code with Memory Indirections Using Polyhedra".** In: Lecture Notes in Computer Science. Springer, 2019, pp. 114–135.

[Bar+22] Haniel Barbosa et al. **"cvc5: A Versatile and Industrial-Strength SMT Solver".** In: Lecture Notes in Computer Science. Springer, 2022, pp. 415–442.

[BBY17] S. Blazy, D. Bühler, and B. Yakobowski. **"Structuring Abstract Interpreters Through State and Value Abstractions".** In: LNCS. Springer, 2017, pp. 112–130.

References – II

[Ber+10] J. Bertrane et al. "Static analysis and verification of aerospace software by abstract interpretation". In: AIAA-2010-3385. 2010.

[BFT16] Clark Barrett, Pascal Fontaine, and Cesare Tinelli. The Satisfiability Modulo Theories Library (SMT-LIB). www.SMT-LIB.org. 2016.

[CDE08] Cristian Cadar, Daniel Dunbar, and Dawson Engler. "KLEE: unassisted and automatic generation of high-coverage tests for complex systems programs". In: 2008.

[Con+18] Sylvain Conchon et al. "Alt-Ergo 2.2". In: Oxford, United Kingdom, July 2018.

References – III

[DOM21] David Delmas, Abdelraouf Ouadjaout, and Antoine Miné. **"Static Analysis of Endian Portability by Abstract Interpretation".** In: Lecture Notes in Computer Science. Springer, 2021, pp. 102–123.

[GKS05] Patrice Godefroid, Nils Klarlund, and Koushik Sen. **"DART: directed automated random testing".** In: ACM, 2005, pp. 213–223.

[Jou+19] M. Journault et al. **"Combinations of reusable abstract domains for a multilingual static analyzer".** In: New York, USA, July 2019, pp. 1–17.

[MB08] Leonardo de Moura and Nikolaj Bjørner. **"Z3: An efficient SMT solver".** In: 2008.

References – IV

[Min17] Antoine Miné. “Tutorial on Static Inference of Numeric Invariants by Abstract Interpretation”. In: Found. Trends Program. Lang. 3-4 (2017), pp. 120–372.

[MM24] Marco Milanese and Antoine Miné. “Generation of Violation Witnesses by Under-Approximating Abstract Interpretation”. In: Lecture Notes in Computer Science. Springer, 2024, pp. 50–73.

[MOM21] R. Monat, A. Ouadjaout, and A. Miné. “A Multilanguage Static Analysis of Python Programs with Native C Extensions”. In: 2021.

References – V

[Mon+24] Raphaël Monat et al. **"Mopsa-C: Improved Verification for C Programs, Simple Validation of Correctness Witnesses (Competition Contribution)".** In: Lecture Notes in Computer Science. Springer, 2024, pp. 387–392.

[OM20] A. Ouadjaout and A. Miné. **"A Library Modeling Language for the Static Analysis of C Programs".** In: ed. by David Pichardie and Mihaela Sighireanu. Lecture Notes in Computer Science. Springer, 2020, pp. 223–247. DOI: `10.1007/978-3-030-65474-0_11`.

[PM24] Francesco Parolini and Antoine Miné. **"Sound Abstract Nonexploitability Analysis".** In: Lecture Notes in Computer Science. Springer, 2024, pp. 314–337.

References – VI

[SMA05] Koushik Sen, Darko Marinov, and Gul Agha. **"CUTE: a concolic unit testing engine for C".** In: ACM, 2005, pp. 263–272. DOI: 10.1145/1081706.1081750.