جامعة نيويورك أبوظبي
NYU ABU DHABI

MoMA LAB

ICSQuartz: Scan Cycle-Aware and Vendor-Agnostic Fuzzing for Industrial Control Systems

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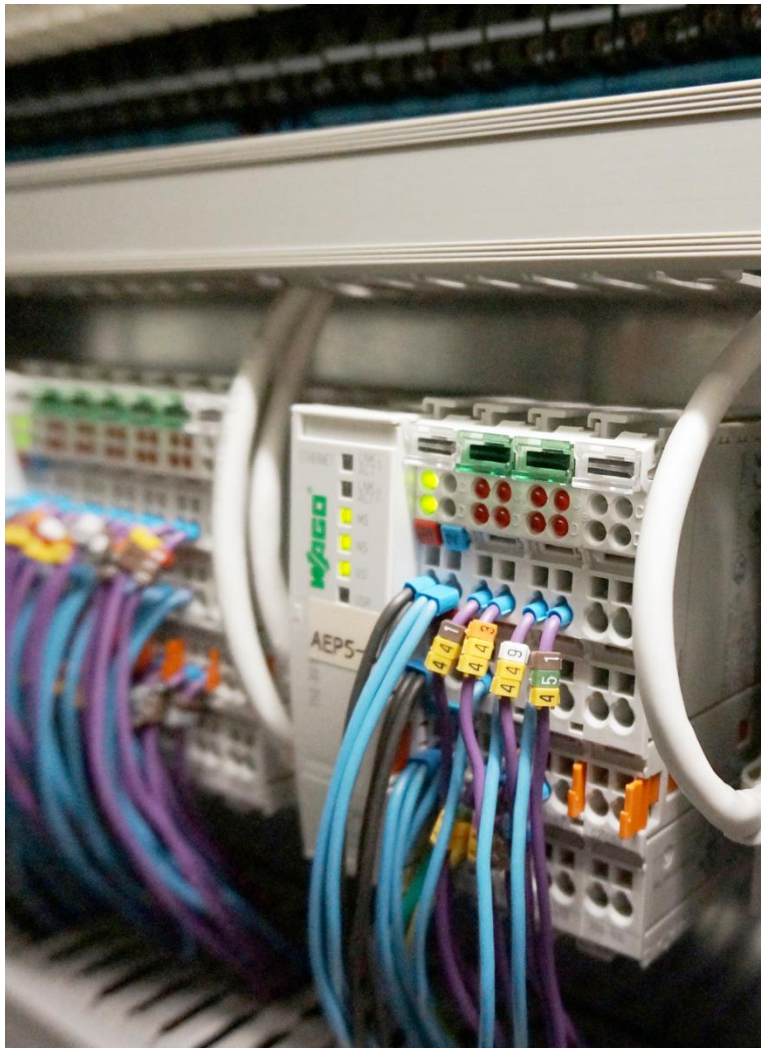
NDSS 2025

02/26/2025

Critical Infrastructure & Industrial Control Systems (ICS)



ICS Under Attack

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Obama Order Sped Up Wave of Cyberattacks Against Iran

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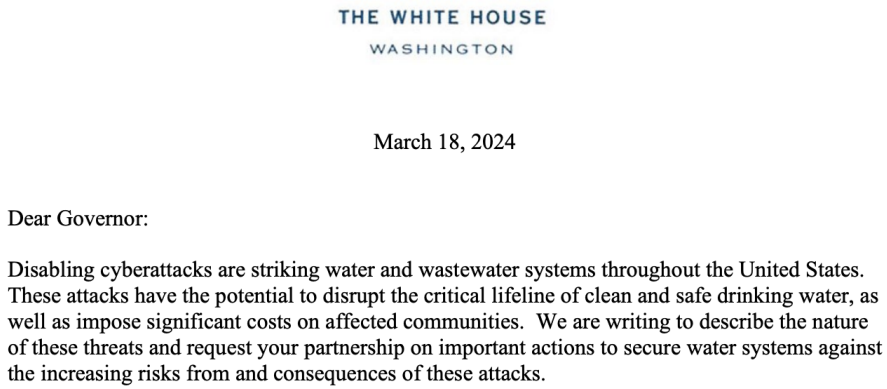
By David E. Sanger

June 1, 2012

WASHINGTON — From his first months in office, President Obama secretly ordered increasingly sophisticated attacks on the computer systems that run Iran's main nuclear enrichment facilities, significantly expanding America's first sustained use of cyberweapons, according to participants in the program.

ICS Under Attack



THE WHITE HOUSE
WASHINGTON

March 18, 2024

Dear Governor:

Disabling cyberattacks are striking water and wastewater systems throughout the United States. These attacks have the potential to disrupt the critical lifeline of clean and safe drinking water, as well as impose significant costs on affected communities. We are writing to describe the nature of these threats and request your partnership on important actions to secure water systems against the increasing risks from and consequences of these attacks.

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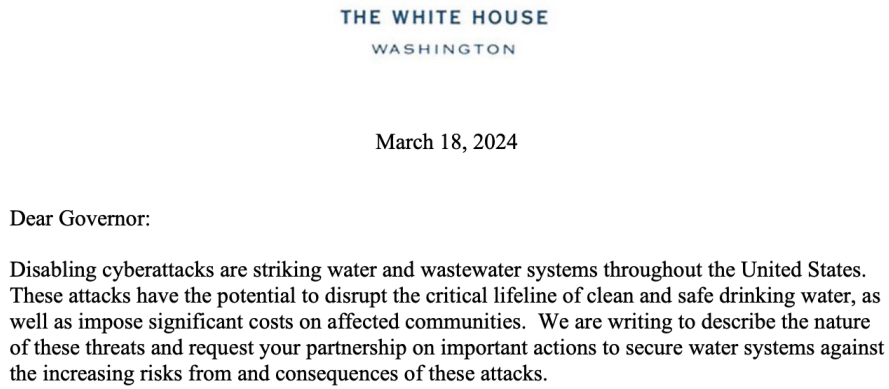

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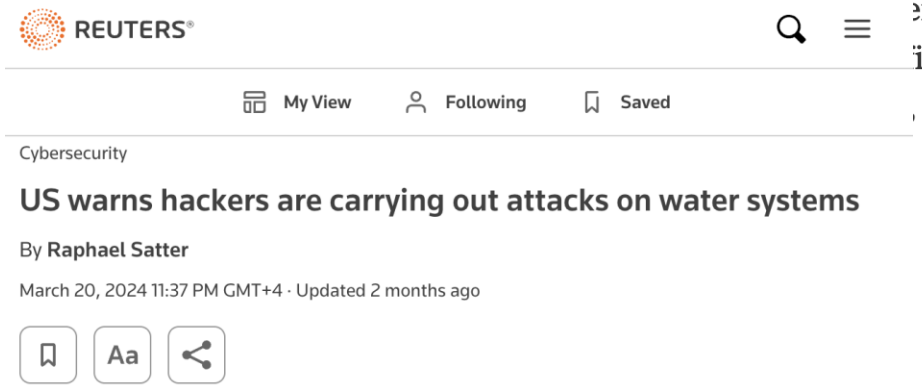

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Cybersecurity

US warns hackers are carrying out attacks on water systems

By **Raphael Satter**

March 20, 2024 11:37 PM GMT+4 · Updated 2 months ago

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JOINT CYBERSECURITY ADVISORY

Co-Authored by:

TLP:CLEAR Product ID: AA24-038A

February 7, 2024

Australian Government Australian Signals Directorate
ASD AUSTRALIAN SIGNALS DIRECTORATE ACSC
Communications Security Establishment Canadian Centre for Cyber Security
Centre de la sécurité des télécommunications Centre canadien pour la cybersécurité
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Menu 360

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America's Cyber Defense Agency
NATIONAL COORDINATOR FOR CRITICAL INFRASTRUCTURE SECURITY AND RESILIENCE

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ALERT

Exploitation of Unitronics PLCs used in Water and Wastewater Systems

Release Date: November 28, 2023

RELATED TOPICS: CYBERSECURITY BEST PRACTICES

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Canadian Centre for Cyber Security
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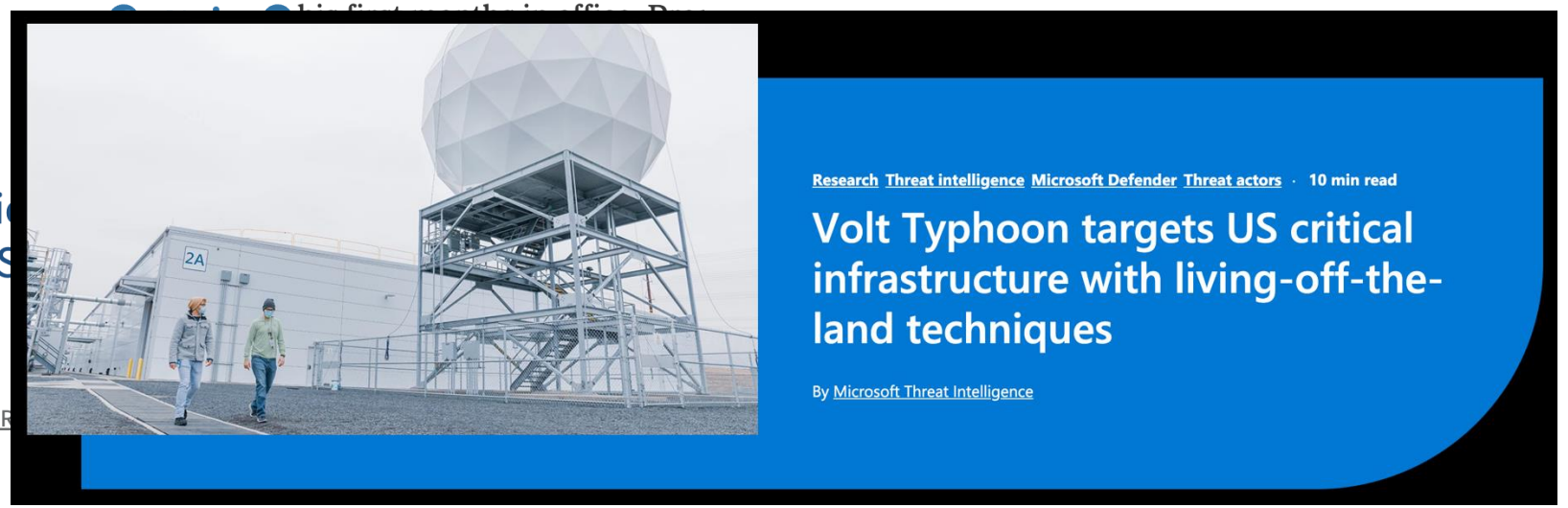

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ICS Security

Why are these systems vulnerable?

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- 4th Industrial Revolution: Operational Technology (OT) merges with IT.

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Why are these systems vulnerable?

- 4th Industrial Revolution: Operational Technology (OT) merges with IT.
- Full-fledged operating systems with IT vulnerabilities.
- Remote monitoring requires network-connected devices.
- ICS software is imperfect, often containing bugs and vulnerabilities.

ICS Software Testing

How can we detect vulnerabilities before they are deployed?

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Software Fuzzing

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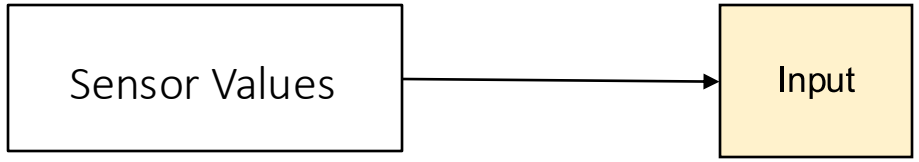
How can we detect vulnerabilities before they are deployed?

Software Fuzzing



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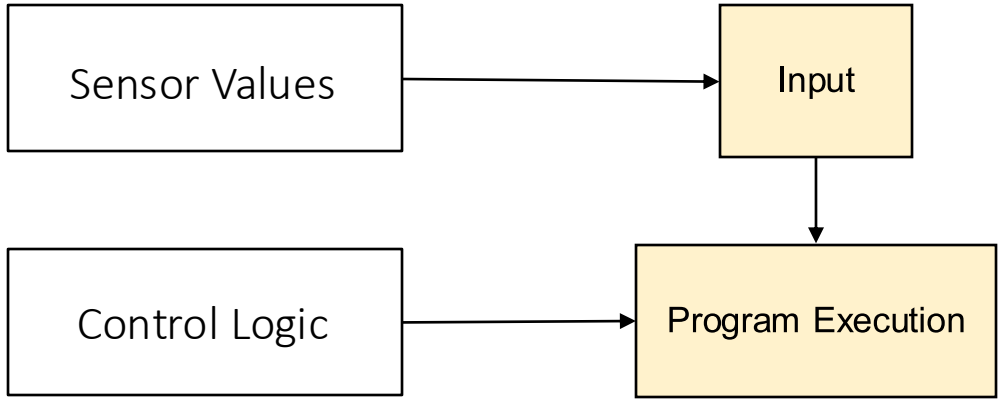

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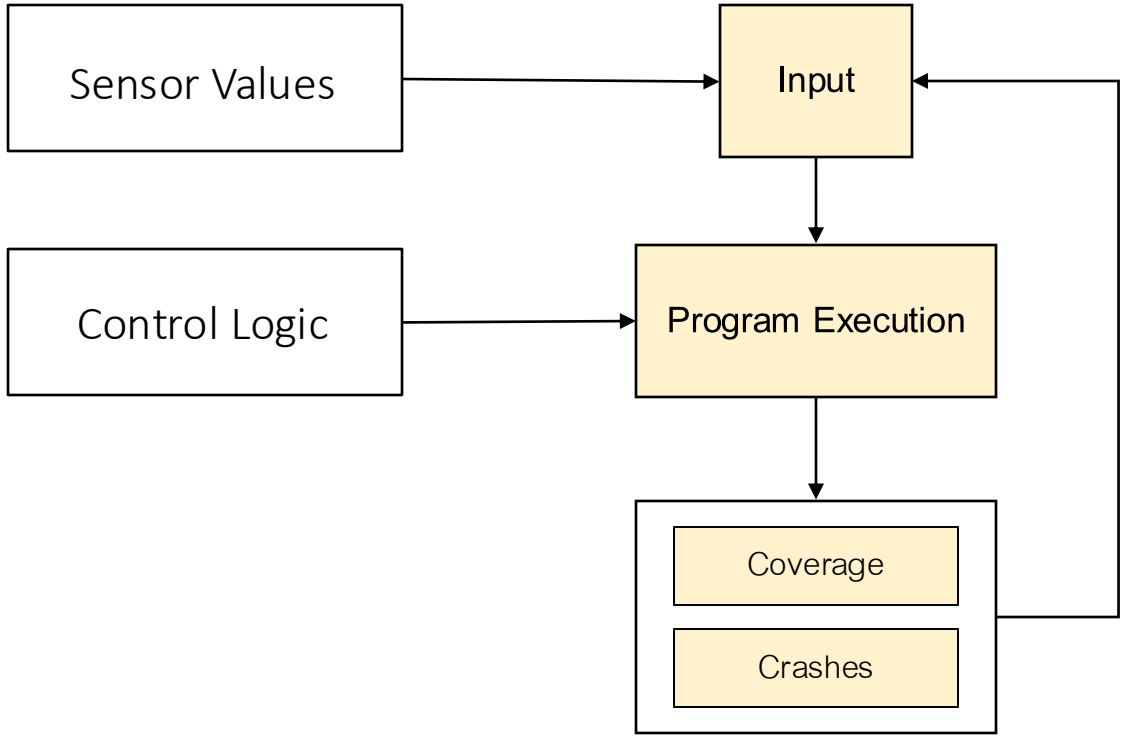
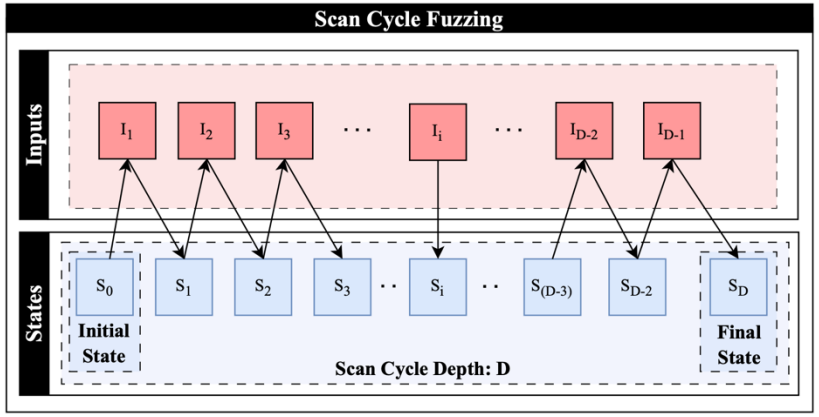


Limitations of State-of-the-Art ICS Fuzzing

- Proprietary compilers, executables
- Vendor-locked solutions
- Imprecise (e.g., address sanitizer)
- Require specific hardware/software
- No scan cycle awareness



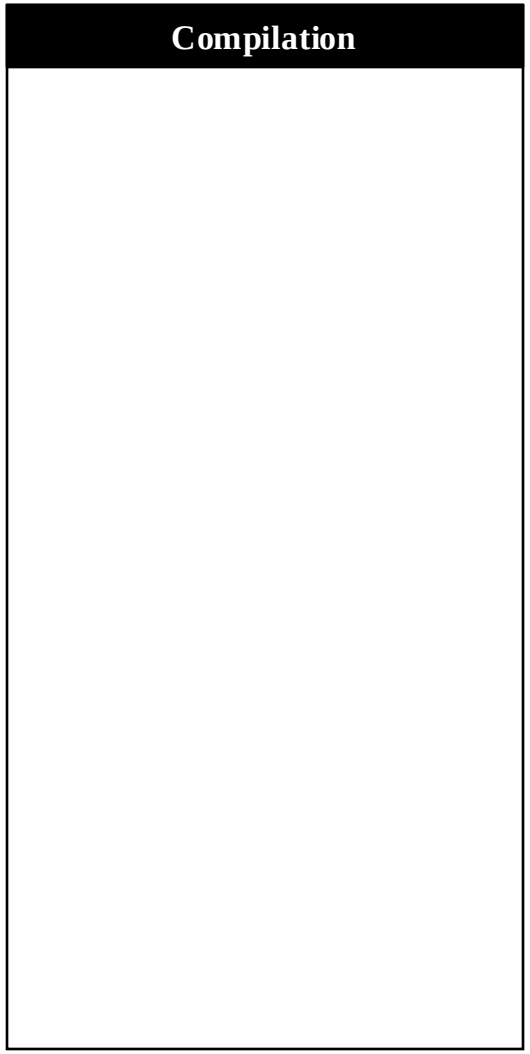
Fuzzing Framework

Existing Projects

Our Contributions

Fuzzing Framework

Existing Projects | Our Contributions



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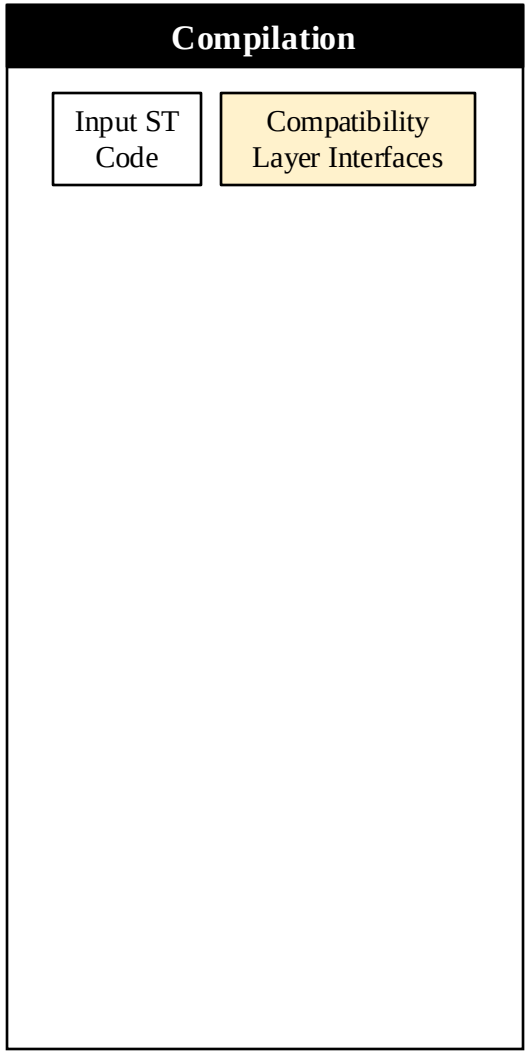

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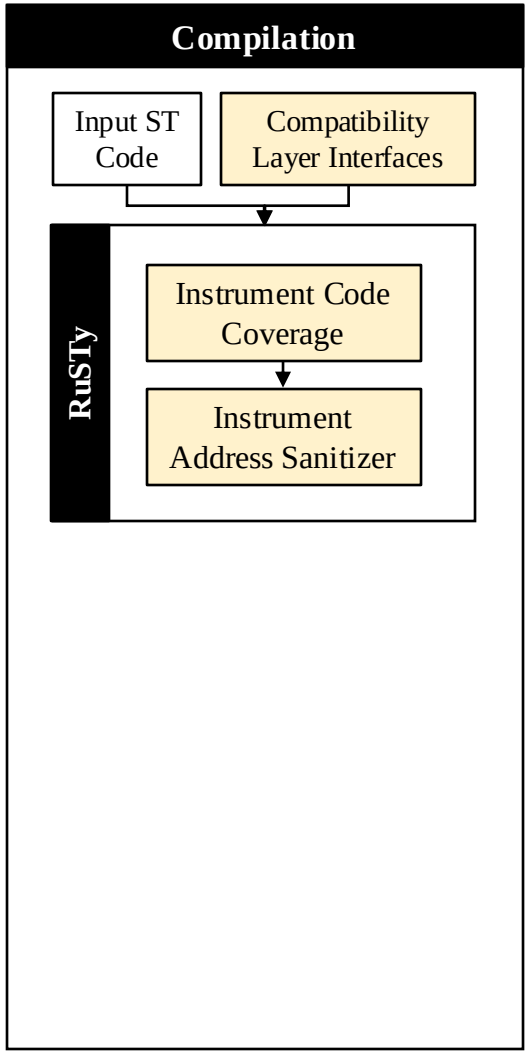

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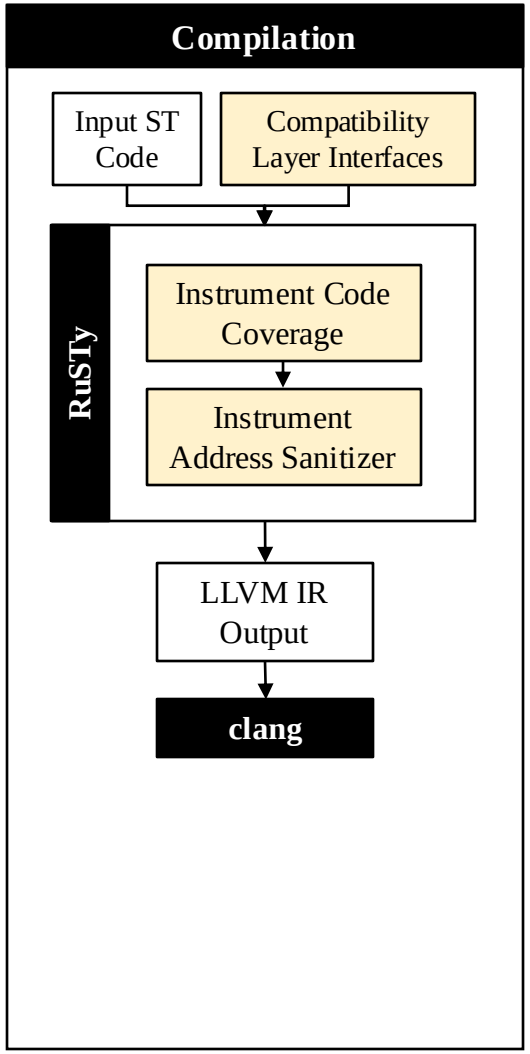

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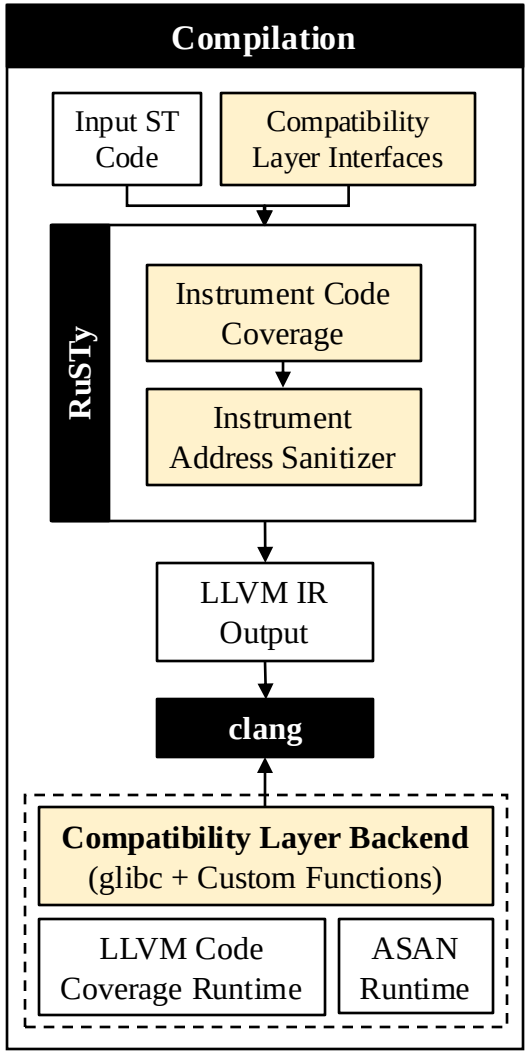

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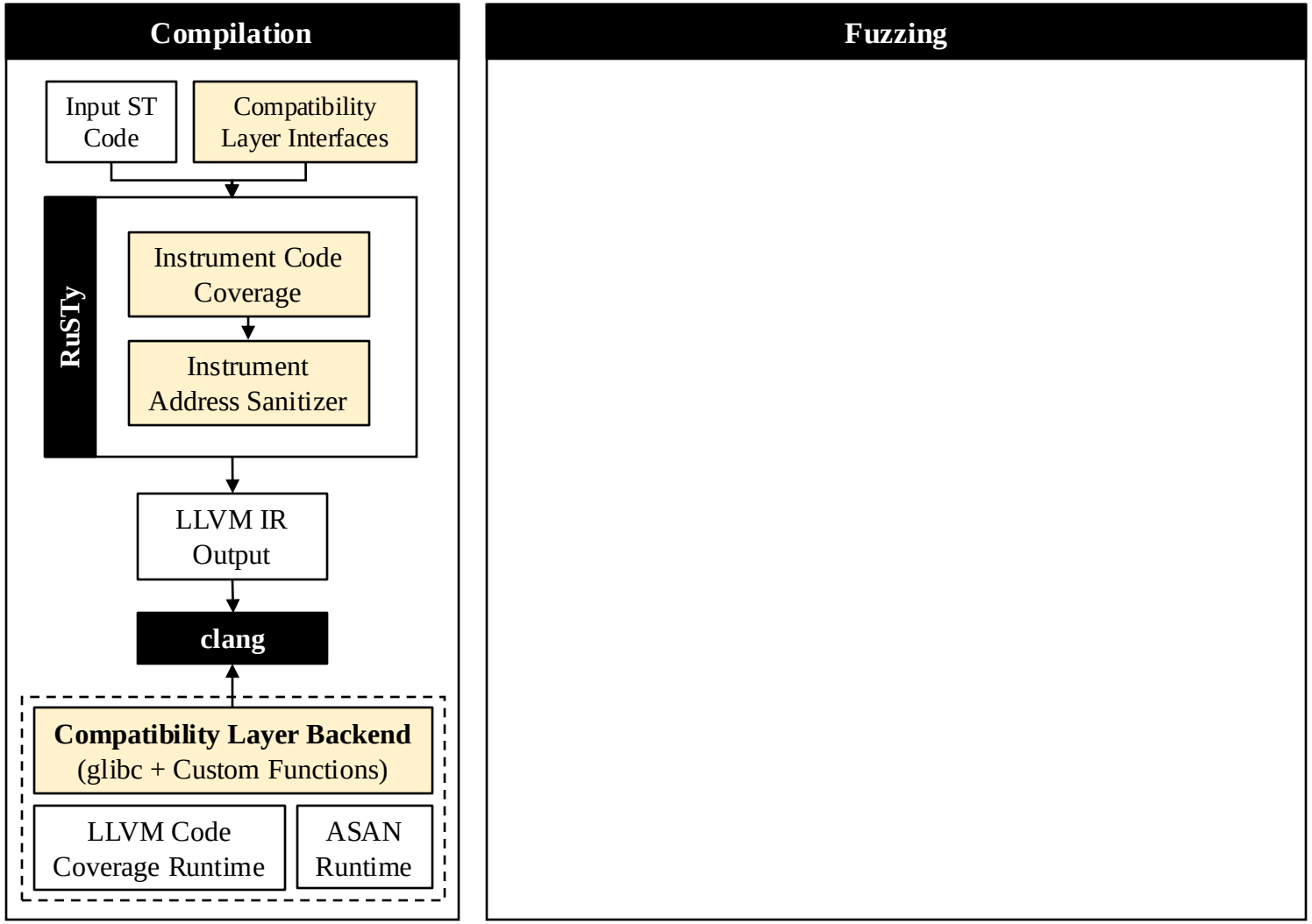

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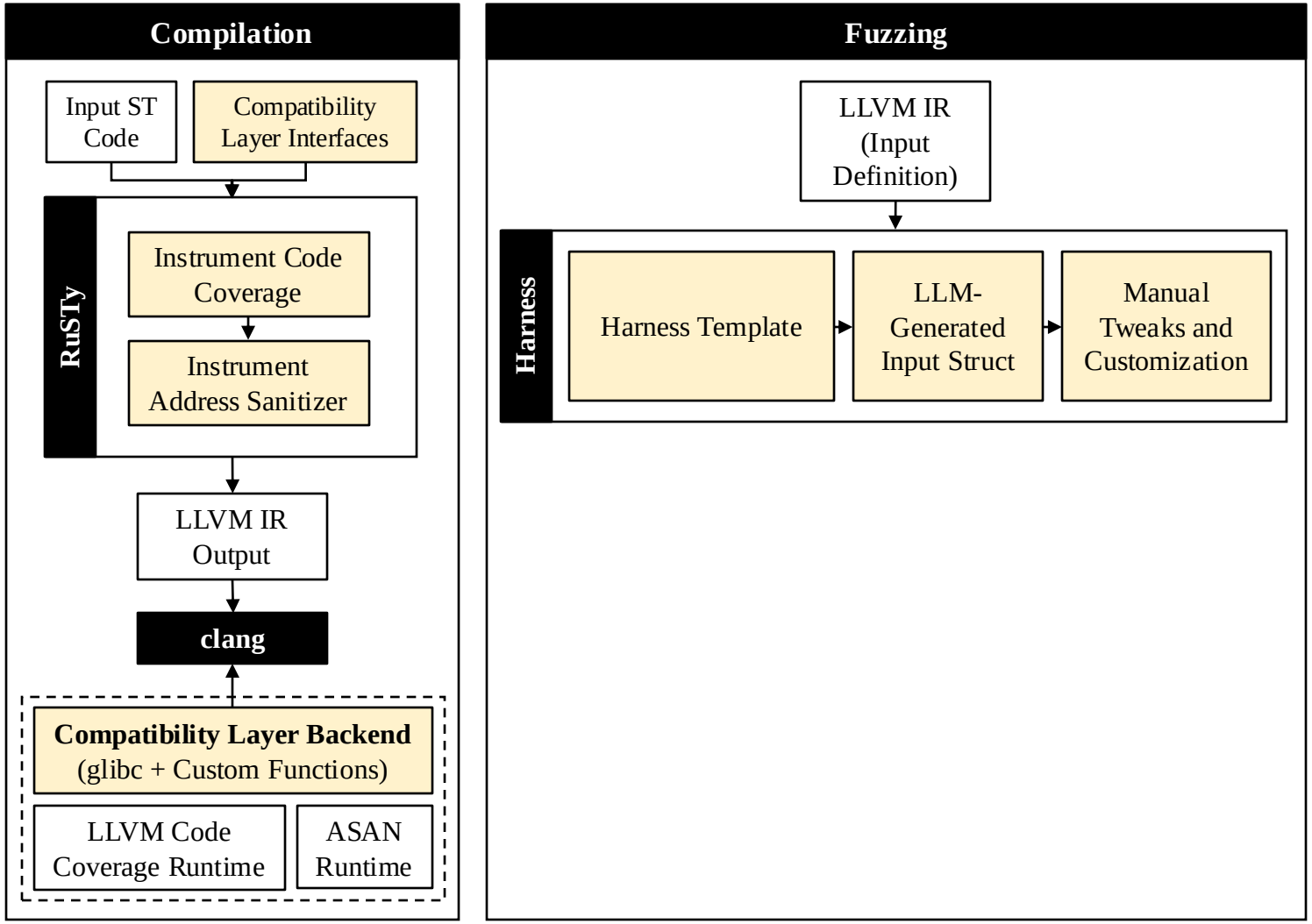

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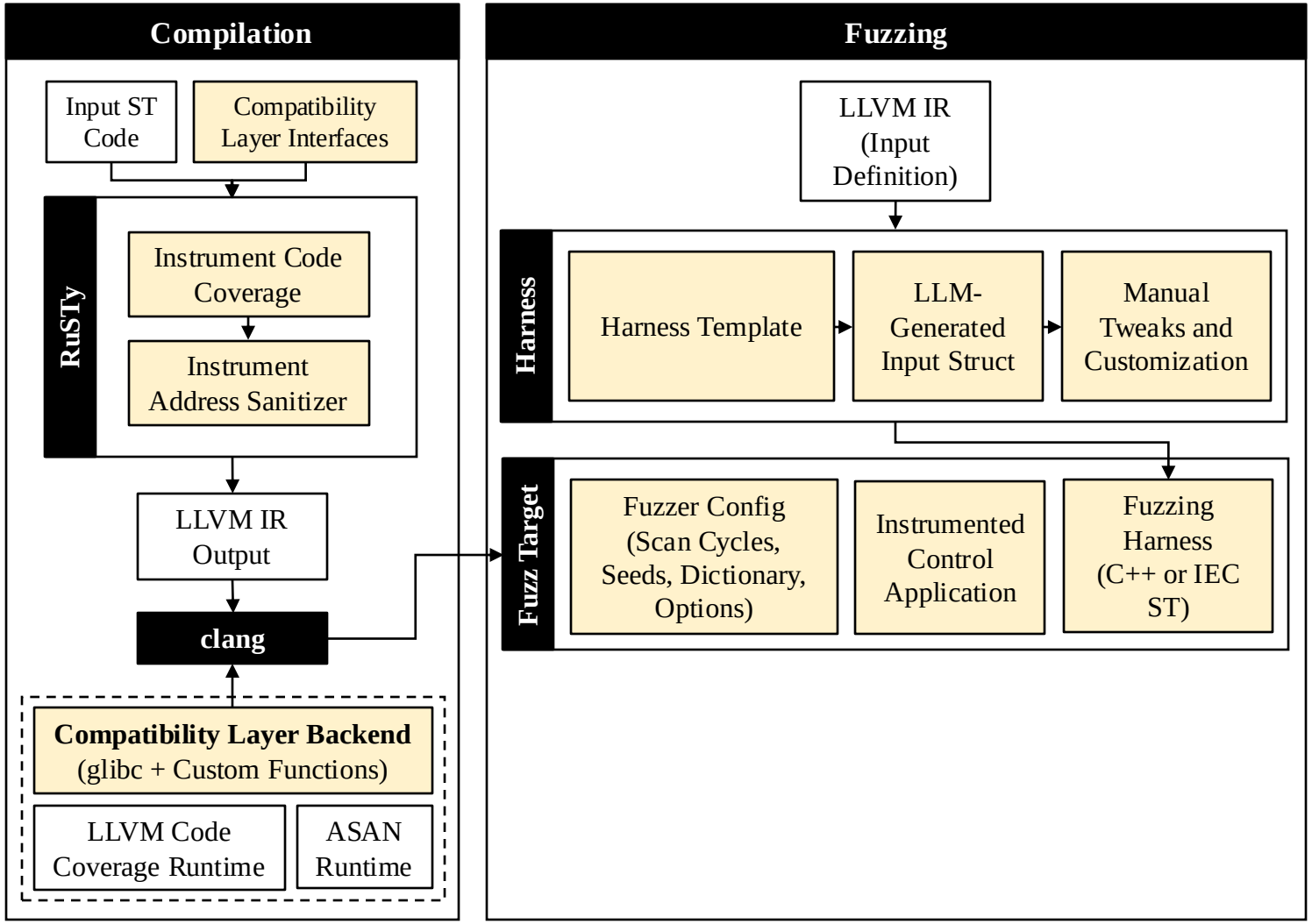

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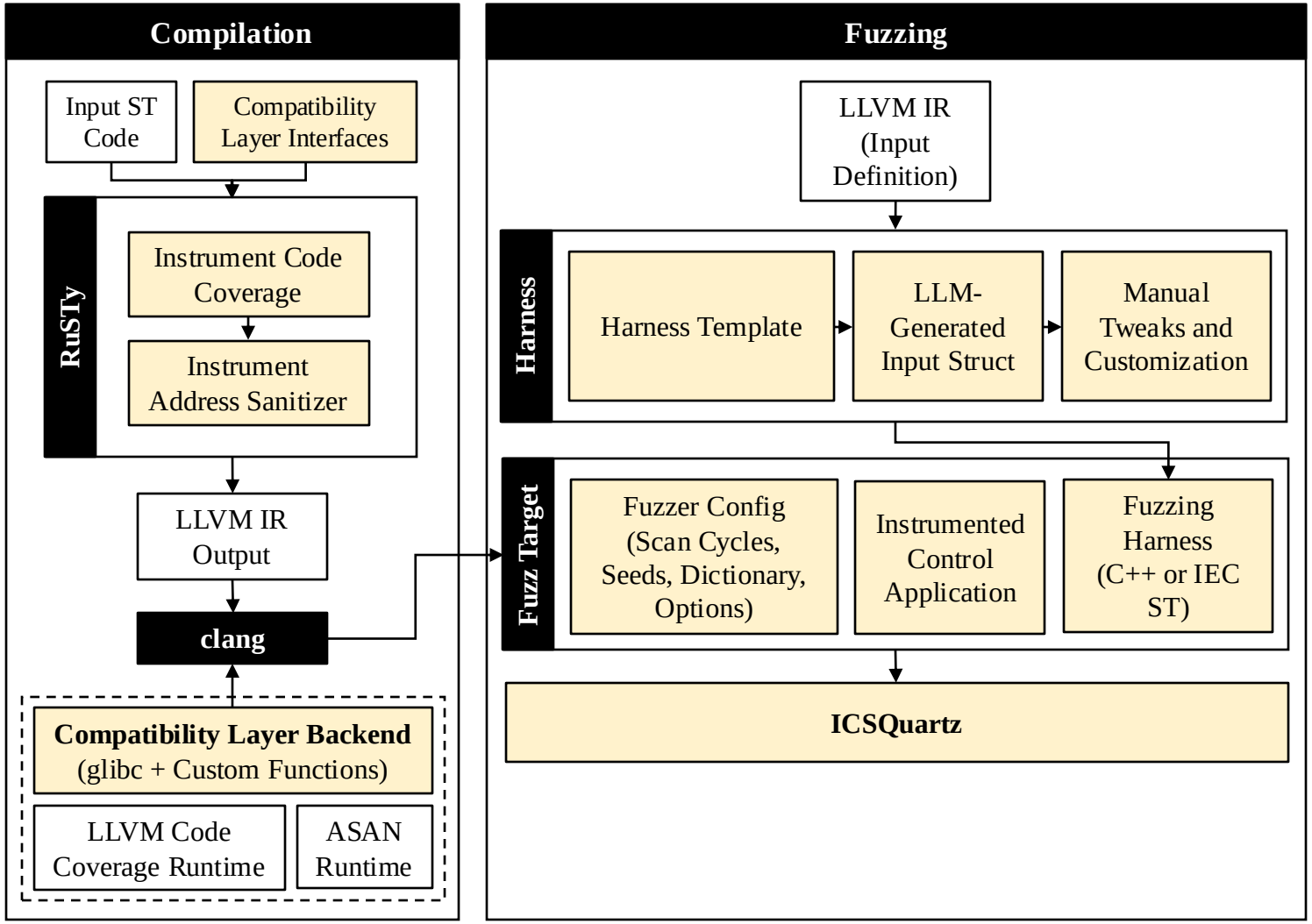

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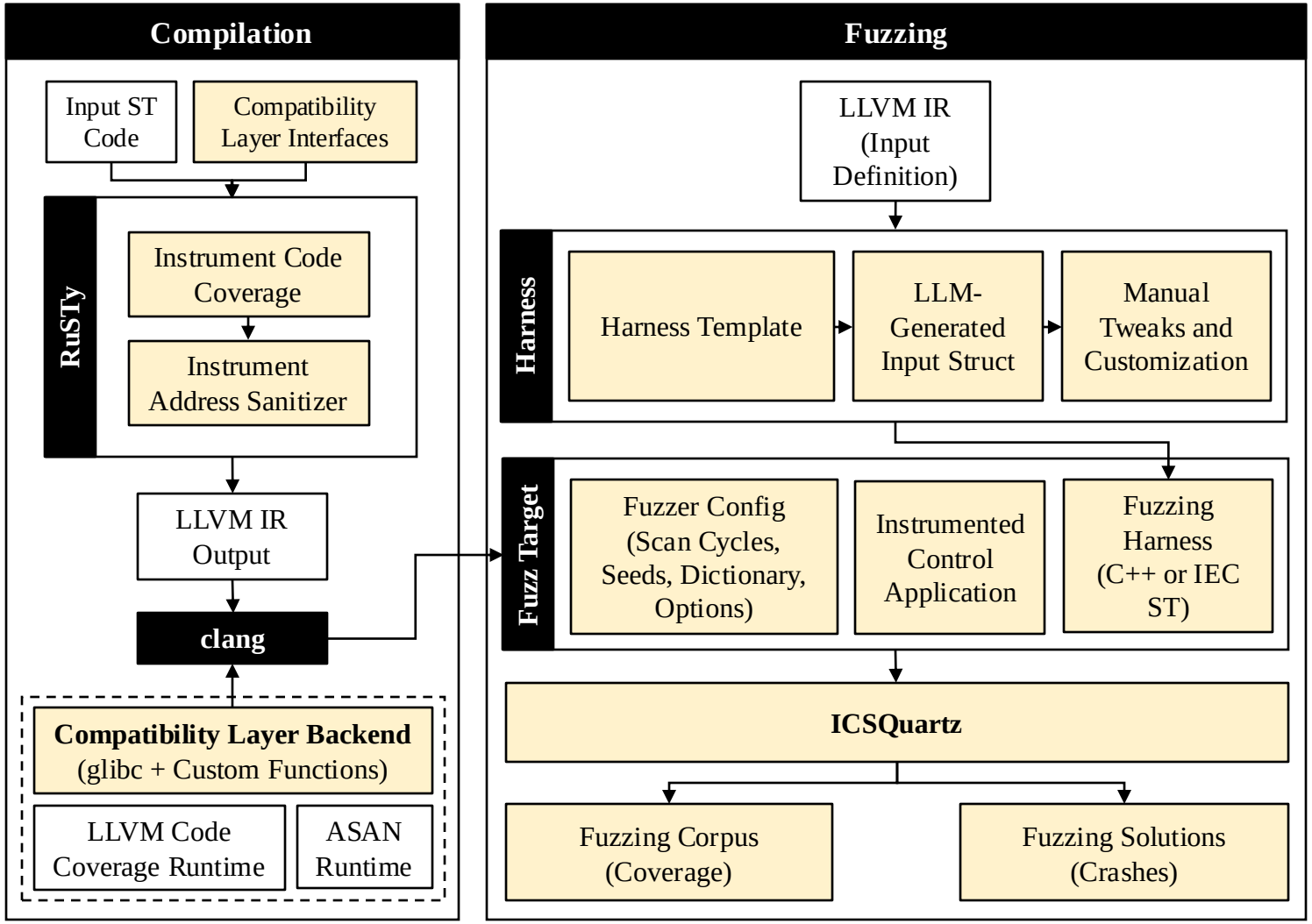

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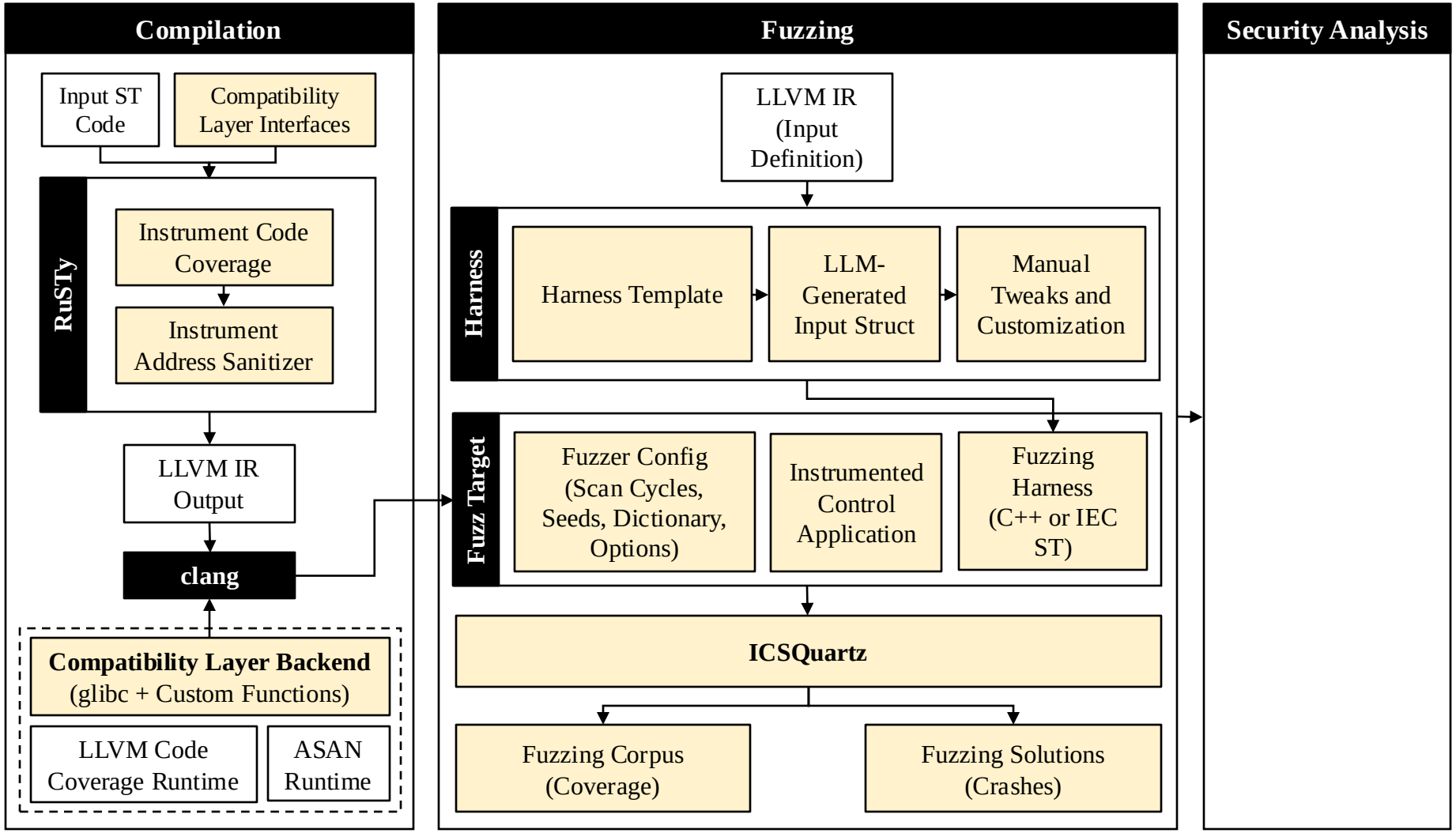

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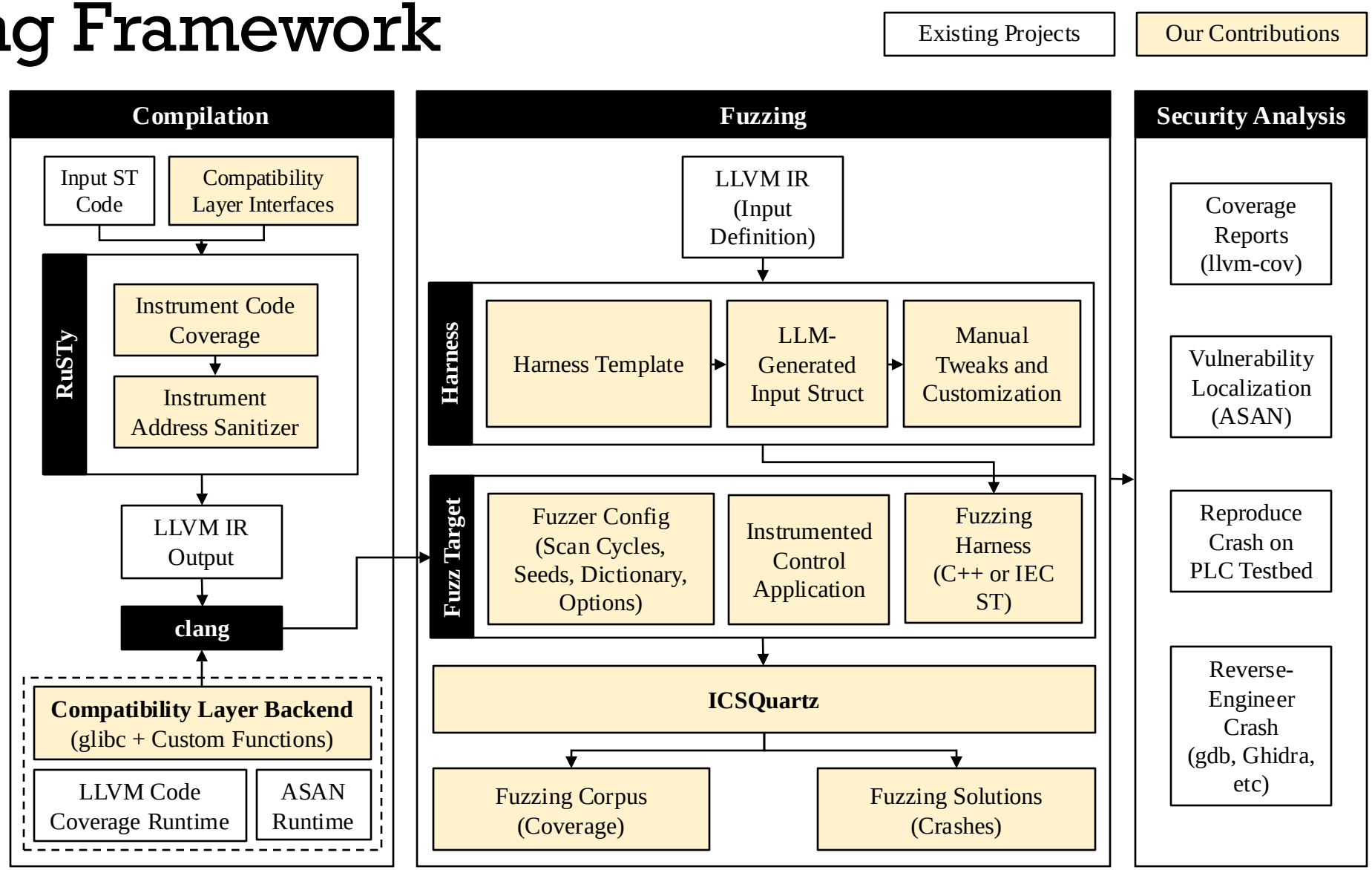

Results: Performance

Order of Magnitude Improvement in Key Metrics.

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Order of Magnitude Improvement in Key Metrics.

Control Application	Execution Speed (inputs/sec)			First Crash (seconds)			First Crash (inputs)		
	ICSQuartz (x64)	FieldFuzz (x64)	ICSFuzz (A8)	ICSQuartz (x64)	FieldFuzz (x64)	ICSFuzz (A8)	ICSQuartz (x64)	FieldFuzz (x64)	ICSFuzz (A8)
bf_mcpy_1	19649.9	593.0	70.9	0.0008	0.25	234	15.7	148	15270
bf_mcpy_6	1403.4	642.4	64.2	0.0140	1.43	188	19.6	898	12172
bf_mcpy_8	1355.6	645.6	66.1	0.0151	7.08	279	20.5	4566	18216
bf_mcpy_12	328.2	526.2	62.1	0.2630	1.95	426	86.3	999	26645
bf_mset_1	7526.0	560.6	64.6	0.0026	0.04	208	19.6	22	13441
bf_mset_3	9961.5	571.2	62.7	0.0020	0.03	174	19.5	17	10906
bf_mset_5	2227.1	503.2	68.8	0.0088	0.56	254	19.6	281	17554
bf_mmove_1	2626.4	660.2	64.6	0.0078	0.005	176	20.5	2	11245
bf_mmove_4	6674.9	578.2	63.1	0.0046	0.003	159	30.5	1	10070
bf_mmove_7	1924.3	573.0	66.3	0.0158	0.005	229	30.5	3	15317
bf_mmove_12	1932.5	508.2	64.5	0.0158	182.14	783	30.5	92456	50643
oob_1_arr_1	21747.2	598.8	71.9	0.0073	0.14	55	159.4	83	3880
oob_1_arr_6	53965.5	591.0	77.0	0.0068	1.39	103	367.1	821	8085
oob_1_arr_13	24039.7	507.0	75.2	0.0071	97.86	207	171.6	49165	27241
oob_2_arr_1	27174.2	520.8	73.5	0.0093	154.42	117	252.0	80080	8558
oob_2_arr_5	53055.0	520.4	71.1	0.0069	155.62	165	367.1	80662	22759
oob_2_arr_13	24999.5	502.2	71.0	0.0054	97.86	192	134.8	48694	13401
Average	15328.88	564.8	68.1	0.0231	41.22	232.29	103.81	21111.65	16788.41

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oob_1_arr_13	24039.7	507.0	75.2	0.0071	97.86	207	171.6	49165	27241
oob_2_arr_1	27174.2	520.8	73.5	0.0093	154.42	117	252.0	80080	8558
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Results: Scan Cycle Mutations

Evaluation of Proposed Mutation Strategies.

Results: Scan Cycle Mutations

Evaluation of Proposed Mutation Strategies.

ICSQuartz vs. SOTA

	Fuzzer	Aircraft Oobr	Aircraft Oobw 4	Aircraft Oobw 5	Anaerobic Oobr 1	Anaerobic Oobr 2	Anaerobic Oobw 1	Anaerobic Oobw 2	Anaerobic Oobw 3	Chemical Oobr 1	Chemical Oobw 1	Smart Grid Oobr 1	Smart Grid Oobw 1
Crashes	ICSQuartz	10	8	10	10	10	5	10	10	10	10	10	10
	AFL++	1	0	0	0	1	0	0	0	0	0	3	1
	FieldFuzz	0	0	9	0	0	0	0	0	0	0	0	0
	ICSFuzz	0	0	0	0	0	0	0	0	0	0	0	0
Time (s)	ICSQuartz	12.4	56.9	0.8	1.5	0.1	30.7	3.1	0.1	0.2	0.2	0.1	0.5
	AFL++	78.8	-	-	-	0.8	-	-	-	-	-	2.4	0.9
	FieldFuzz	-	-	42.5	-	-	-	-	-	-	-	-	-
	ICSFuzz	-	-	-	-	-	-	-	-	-	-	-	-
Execs.	ICSQuartz	5.6M	14M	95k	560k	1.0k	14M	480k	240	1.6k	6.1k	2.4k	100k
	AFL++	32k	-	-	-	1.3k	-	-	-	-	-	1.6k	2.1k
	FieldFuzz	-	-	2.7k	-	-	-	-	-	-	-	-	-
	ICSFuzz	-	-	-	-	-	-	-	-	-	-	-	-

TABLE V: **Scan Cycle Benchmark Evaluation (10 Trials).**

Results: Scan Cycle Mutations

Evaluation of Proposed Mutation Strategies.

ICSQuartz vs. SOTA

	Fuzzer	Aircraft Oobr	Aircraft Oobw 4	Aircraft Oobw 5	Anaerobic Oobr 1	Anaerobic Oobr 2	Anaerobic Oobw 1	Anaerobic Oobw 2	Anaerobic Oobw 3	Chemical Oobr 1	Chemical Oobw 1	Smart Grid Oobr 1	Smart Grid Oobw 1
Crashes	ICSQuartz	10	8	10	10	10	5	10	10	10	10	10	10
	AFL++	1	0	0	0	1	0	0	0	0	0	3	1
	FieldFuzz	0	0	9	0	0	0	0	0	0	0	0	0
	ICSFuzz	0	0	0	0	0	0	0	0	0	0	0	0
Time (s)	ICSQuartz	12.4	56.9	0.8	1.5	0.1	30.7	3.1	0.1	0.2	0.2	0.1	0.5
	AFL++	78.8	-	-	-	0.8	-	-	-	-	-	2.4	0.9
	FieldFuzz	-	-	42.5	-	-	-	-	-	-	-	-	-
	ICSFuzz	-	-	-	-	-	-	-	-	-	-	-	-
Execs.	ICSQuartz	5.6M	14M	95k	560k	1.0k	14M	480k	240	1.6k	6.1k	2.4k	100k
	AFL++	32k	-	-	-	1.3k	-	-	-	-	-	1.6k	2.1k
	FieldFuzz	-	-	2.7k	-	-	-	-	-	-	-	-	-
	ICSFuzz	-	-	-	-	-	-	-	-	-	-	-	-

TABLE V: **Scan Cycle Benchmark Evaluation (10 Trials).**

Results: Scan Cycle Mutations

Evaluation of Proposed Mutation Strategies.

ICSQuartz vs. SOTA

	Fuzzer	Aircraft Oobr	Aircraft Oobw 4	Aircraft Oobw 5	Anaerobic Oobr 1	Anaerobic Oobr 2	Anaerobic Oobw 1	Anaerobic Oobw 2	Anaerobic Oobw 3	Chemical Oobr 1	Chemical Oobw 1	Smart Grid Oobr 1	Smart Grid Oobw 1
Crashes	ICSQuartz	10	8	10	10	10	5	10	10	10	10	10	10
	AFL++	1	0	0	0	1	0	0	0	0	0	3	1
	FieldFuzz	0	0	9	0	0	0	0	0	0	0	0	0
	ICSFuzz	0	0	0	0	0	0	0	0	0	0	0	0
Time (s)	ICSQuartz	12.4	56.9	0.8	1.5	0.1	30.7	3.1	0.1	0.2	0.2	0.1	0.5
	AFL++	78.8	-	-	-	0.8	-	-	-	-	-	2.4	0.9
	FieldFuzz	-	-	42.5	-	-	-	-	-	-	-	-	-
	ICSFuzz	-	-	-	-	-	-	-	-	-	-	-	-
Execs.	ICSQuartz	5.6M	14M	95k	560k	1.0k	14M	480k	240	1.6k	6.1k	2.4k	100k
	AFL++	32k	-	-	-	1.3k	-	-	-	-	-	1.6k	2.1k
	FieldFuzz	-	-	2.7k	-	-	-	-	-	-	-	-	-
	ICSFuzz	-	-	-	-	-	-	-	-	-	-	-	-

TABLE V: **Scan Cycle Benchmark Evaluation (10 Trials).**

Toggled Mutation Strategies

	ICSQuartz Scan Cycle Mutations	Aircraft Oobr	Aircraft Oobw 4	Aircraft Oobw 5	Anaerobic Oobr 1	Anaerobic Oobr 2	Anaerobic Oobw 1	Anaerobic Oobw 2	Anaerobic Oobw 3	Chemical Oobr 1	Chemical Oobw 1	Smart Grid Oobr 1	Smart Grid Oobw 1
Total Crashes	●	10	8	10	10	10	5	10	10	10	10	10	10
	○	0	0	0	0	1	0	0	0	0	0	0	0
Stale Cycles	●	1.9	20.9	31.3	1.0	1.5	1.3	40.5	30.2	3.1	3.1	6.6	1.9
	○	99.9	99.9	44.0	99.9	99.9	99.9	99.9	99.9	5.4	99.9	99.9	99.9

TABLE VI: **Evaluation of ICSQuartz Mutations (10 Trials).**

Results: Scan Cycle Mutations

Evaluation of Proposed Mutation Strategies.

ICSQuartz vs. SOTA

	Fuzzer	Aircraft Oobr	Aircraft Oobw 4	Aircraft Oobw 5	Anaerobic Oobr 1	Anaerobic Oobr 2	Anaerobic Oobw 1	Anaerobic Oobw 2	Anaerobic Oobw 3	Chemical Oobr 1	Chemical Oobw 1	Smart Grid Oobr 1	Smart Grid Oobw 1
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	AFL++	1	0	0	0	1	0	0	0	0	0	3	1
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	AFL++	78.8	-	-	-	0.8	-	-	-	-	-	2.4	0.9
	FieldFuzz	-	-	42.5	-	-	-	-	-	-	-	-	-
	ICSFuzz	-	-	-	-	-	-	-	-	-	-	-	-
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	FieldFuzz	-	-	2.7k	-	-	-	-	-	-	-	-	-
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TABLE V: **Scan Cycle Benchmark Evaluation (10 Trials).**

Toggled Mutation Strategies

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Total Crashes	●	10	8	10	10	10	5	10	10	10	10	10	10
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	○	99.9	99.9	44.0	99.9	99.9	99.9	99.9	99.9	5.4	99.9	99.9	99.9

TABLE VI: **Evaluation of ICSQuartz Mutations (10 Trials).**

Results: Impact

Results: Impact

Real-World Fuzz Campaign

OSCAT Program	Total Executions		
	ICSQuartz	FieldFuzz	ICSFuzz
CHARNAME	123M	239k	102k
CLEAN	3.73M	239k	99.2k
DEL_CHARS	3.73M	239k	99.6k
DT_TO_STRF	129k	239k	102k
FIND_CHAR	*386k*	239k	102k
FIND_CTRL	*386k*	239k	99.1k
FINDB_NONUM	*436k*	239k	99.1k
FINDB_NUM	*436k*	239k	99.5k
FSTRING_TO_BYTE	817k	239k	99.3k
FSTRING_TO_DWORD	333k	239k	99.0k
IS_CC	3.73M	239k	99.2k
IS_NCC	3.73M	239k	99.3k
MIRROR	*436k*	239k	99.7k
MONTH_TO_STRING	**1.07B**	239k	102k
REAL_TO_STRF	399M	239k	102k
REPLACE_ALL	23.7M	239k	100k
REPLACE_CHARS	23.7M	239k	99.2k
TRIM	436k	240k	100k
TRIM1	436k	239k	99.3k
TRIME	436k	239k	100k
UPPER_CASE	436k	239k	99.7k
WEEKDAY_TO_STRING	966M	240k	102k
BASE64_ENCODE_STR	17.9k	N/A	N/A
XML_READER	*644k*	N/A	N/A

TABLE IV: **OSCAT Fuzzing Campaign. Bold** indicates a vendor-agnostic CVE issued (discovered only by ICSQuartz). *Italics* indicate a RuSTy-specific compiler vulnerability.

Results: Impact

Real-World Fuzz Campaign

OSCAT Program	Total Executions		
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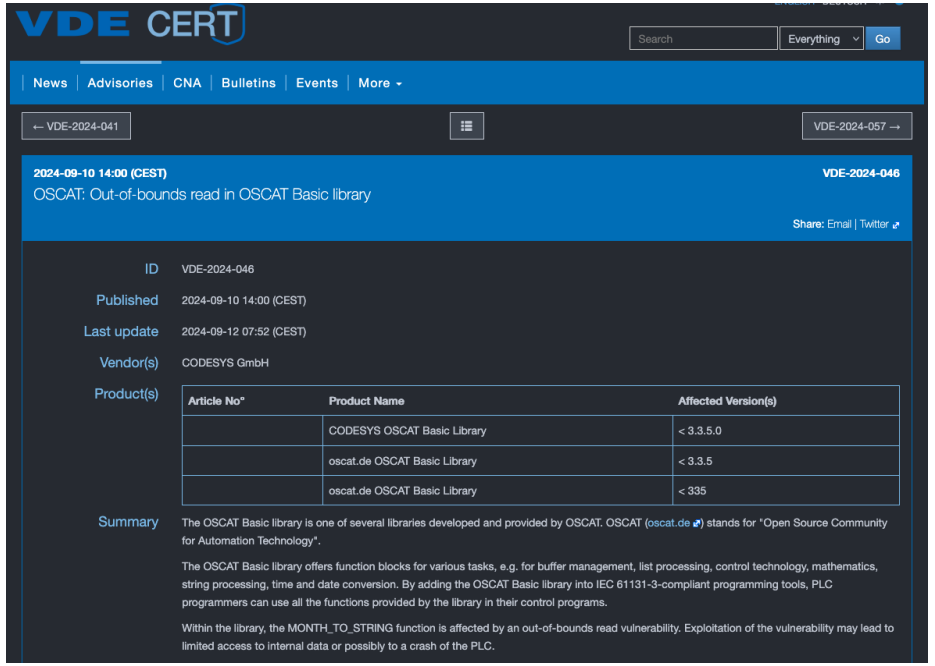
Disclosed CVE-2024-6876



Key Takeaways:

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- First native fuzzer for ICS programs (IEC-61131-3 Structured Text):
  - Surpasses black-box state-of-the-art solutions by an order of magnitude in performance.
  - Provides increased precision for code coverage and vulnerability detection.

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Key Takeaways:

- First native fuzzer for ICS programs (IEC-61131-3 Structured Text):
  - Surpasses black-box state-of-the-art solutions by an order of magnitude in performance.
  - Provides increased precision for code coverage and vulnerability detection.
- Introduces novel ICS-specific scan cycle mutation strategies:
  - Detect vulnerabilities not discovered by prior work.
  - Release new scan cycle benchmarks.
- Discover and disclose:
  - The first (to our knowledge) Structured Text CVE.
  - Compiler bug in RuSTy ICS compiler.

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Thank you

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