CASTLE: Benchmarking Dataset for Static Code Analyzers and LLMs towards CWE Detection

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Motivation & Problem

- Vulnerabilities in code cause more than a **billion** of users' data to be **exposed** each year. A 1.5 times increase year over year [1].
- Yearly **CVE** releases have tripled since 2017 to around **40,000** in 2024 [2].
- Traditional tools (SAST, formal verification) are widely used to detect faults, but their **effectiveness varies greatly**.
- Uncertainty on what types of **CWE** are covered and how well are they covered by such tools.
- Can **LLMs** be effective tools to augment or replace traditional static analysis?
- How effective are tool **combinations**? What are the best combinations?
- Lack of standardized **metrics** to evaluate single or tool combinations.

[1] Ani Petrosyan, Statista, Annual number of data compromises and individuals impacted in the United States from 2005 to 2024
[2] Kaaviya, cyberpress.org, Over 40,000 CVEs Published in 2024, Marking a 38% Increase from 2023

Research Questions

RQ1: How do state-of-the-art static analysis tools, formal verification methods, and LLM-based approaches compare to effectively detecting C code vulnerabilities?

RQ2: Are combinations of tools more effective than using a single tool?

RQ3: What metrics can reliably demonstrate these differences among various tools?

Bad API Documentation

No Trial

Closed-source tools

Slow Runtime

No CLI interface

Cloud Connection

Restrictive ToS

Errors in code

Trial license

Contact Sales...

No viable dataset

Bugs in C software

Rate limits

API Costs

Mandatory repositories

Custom output formats

Missing Finding Properties

What is a Weakness?

Is there a vulnerability in this snippet?

Yes, technically `printf` can return an error and we did not handle it.

```c
#include <stdio.h>
#include <stdlib.h>

int main() {
    int *A = (int*) malloc(sizeof(int) * 10);

    if (A == NULL) {
        printf("Failed to allocate memory.\n");
        return 1;
    }

    for (int i = 1; i <= 4; i++) {
        A[i] = i;
        printf("%d\n", A[i]);
    }

    free(A);
    return 0;
}
```

Common Weakness Enumeration

CWE is a standardized system that categorizes and defines software and hardware security weaknesses to facilitate consistent vulnerability identification, assessment, and mitigation across tools and organizations.

https://cwe.mitre.org/

CWE	Top 25 Rank	Vulnerability Description
CWE-22	5	Improper Limitation of a Pathname to a Restricted Directory
CWE-78	7	Improper Neutralization of Special Elements used in an OS Command
CWE-89	3	Improper Neutralization of Special Elements used in an SQL Command
CWE-125	6	Out-of-bounds Read
CWE-134	12	Use of Externally-Controlled Format String
CWE-190	23	Integer Overflow or Wraparound
CWE-253	-	Incorrect Check of Function Return Value
CWE-327	-	Use of a Broken or Risky Cryptographic Algorithm
CWE-362	-	Concurrent Execution using Shared Resource with Improper Synchronization
CWE-369	23	Divide By Zero
CWE-401	-	Missing Release of Memory after Effective Lifetime
CWE-415	21	Double Free
CWE-416	8	Use After Free
CWE-476	21	NULL Pointer Dereference
CWE-522	14	Insufficiently Protected Credentials
CWE-617	-	Reachable Assertion
CWE-628	-	Function Call with Incorrectly Specified Arguments
CWE-674	24	Uncontrolled Recursion
CWE-761	20	Free of Pointer not at Start of Buffer
CWE-770	24	Allocation of Resources Without Limits or Throttling
CWE-787	2	Out-of-bounds Write
CWE-798	14	Use of Hard-coded Credentials
CWE-822	20	Untrusted Pointer Dereference
CWE-835	24	Loop with Unreachable Exit Condition
CWE-843	-	Access of Resource Using Incompatible Type

Types of Static Analysis

Aspect	Stati Application Security Testing (SAST)	Formal Verification (FV)	Large Language Model (LLM)
Approach	Rule-based pattern matching, data flow analysis, taint analysis	Mathematical proofs of correctness	AI-based pattern recognition and reasoning
Strengths	• Fast runtime • Broad coverage • Easy integration	• Low false positives • Verification guarantees	• High adaptability • Detection without explicit rules
Weaknesses	• High false positive rate • Limited semantic reasoning	• Limited scalability with codebase size • Inability to detect non-formal issues	• Limited context window • Price • Hallucinations and false positives

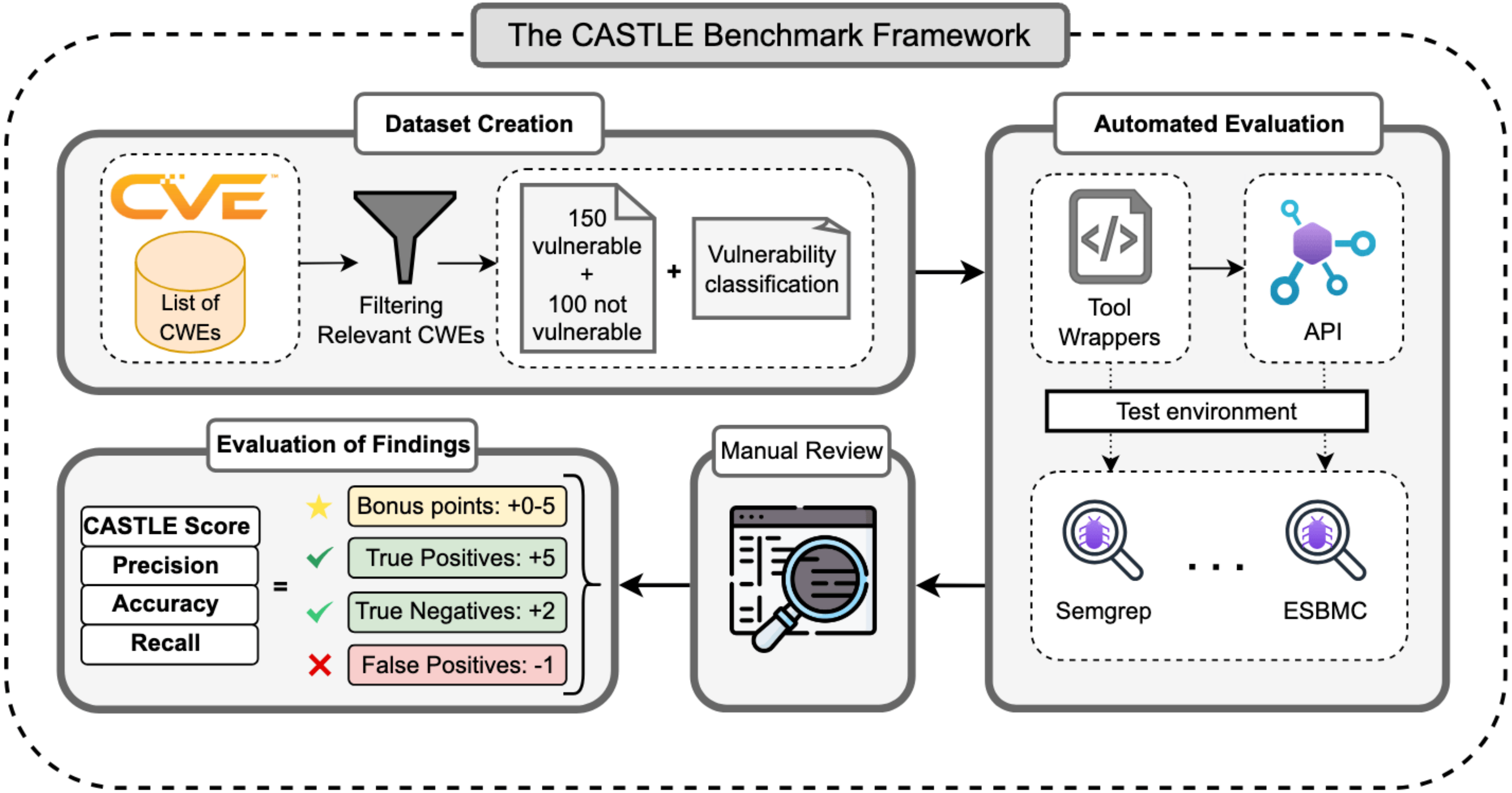
Existing Datasets

Dataset	Size	#Multiple Vuln./File	Vuln. Snippets	Compilable	Granularity	Labelling	Source
Draper [7]	1274k	✔	5.62%	✘	function	Stat	mixed
Big-Vul [8]	264k	✘	100%	✘	function	Patch	real-world
DiverseVul [9]	349k	✘	7.02%	✘	function	Patch	real-world
FormAI-v2 [2]	331k	✔	62.07%	✔	file	FV	AI Gen.
PrimeVul [10]	235k	✘	3%	✘	function	Manual	real-world
SARD [11]	101k	✘	100%	✔	file	B/S/M	mixed
Juliet (C/C++) [12]	64k	✘	100%	✔	file	BDV	synthetic
Devign [13]	28k	✘	46.05%	✘	function	Manual	real-world
REVEAL [14]	23k	✘	9.85%	✘	function	Patch	real-world
CVEfixes [15]	20k	✘	100%	✘	commit	Patch	real-world

What is CASTLE?

CASTLE: CWE Automated Security Testing and Low-level Evaluation

- A benchmarking framework to test static code analyzers
- Consists of 250 compilable, labeled C applications, with 10,000+ LoC
- 150 (60%) of the hand-crafted applications contain one weakness (25 CWEs)
- Wrappers for automated tool evaluation (container, API, report)
- CASTLE Score metric for opinionated evaluation
- CASTLE Combination Score for evaluation of tool combinations



The CASTLE Benchmark Framework
Dataset Creation
CVE
List of CWEs
Filtering Relevant CWEs
150 vulnerable + 100 not vulnerable
+
Vulnerability classification
Automated Evaluation
Tool Wrappers
API
Test environment
Semgrep
...
ESBMC
Manual Review
Evaluation of Findings
CASTLE Score
Precision
Accuracy
Recall
=
Bonus points: +0-5
True Positives: +5
True Negatives: +2
False Positives: -1

Example test (CASTLE-787-1.c)

```c
/*
============================================================================
dataset: CASTLE-Benchmark
name: CASTLE-787-1.c
version: 1.1
compile: gcc CASTLE-787-1.c -o CASTLE-787-1
vulnerable: true
description: Buffer overflow in scanf function.
cwe: 787
============================================================================
*/
#include <stdio.h>

int main( int argc, char *argv[])
{
    char reg_name[12];
    printf("Enter your username:");
    scanf("%s", reg_name); // {!LINE}
    printf("Hello %s.\n",reg_name);
    return 0;
}
```

The CASTLE Metric

Let:

- t: tool (SAST, FV, LLM)
- d: tests
- d_i, weakness in test i
- v_i, correct weakness label for test I
- t_{cwe}, position of a CWE in the MITRE top list

Bonus Point Formula

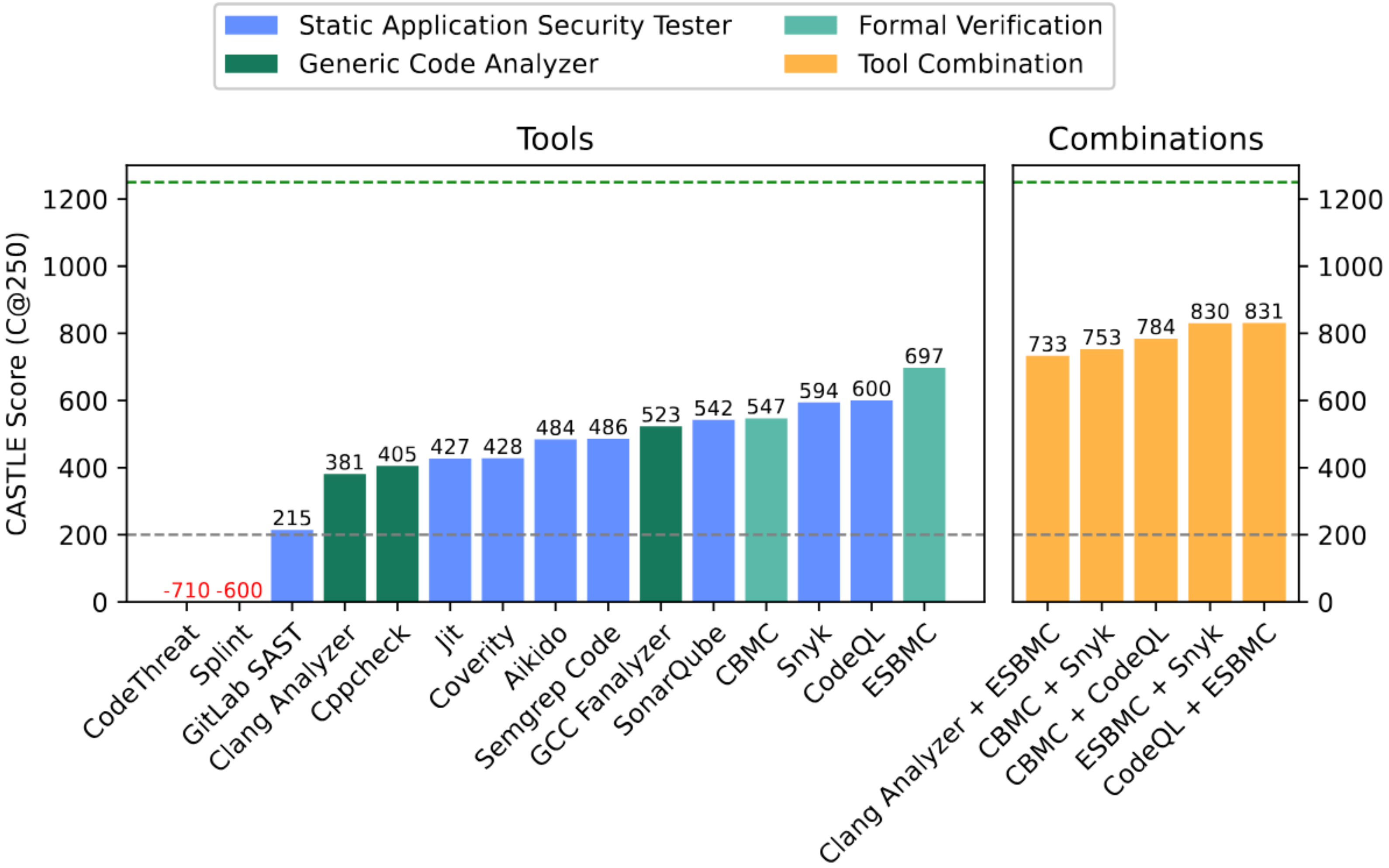
$$B(t_{cwe}) = \begin{cases} b_{\max} - \left\lfloor \frac{S(t_{cwe})-1}{b_{\max}} \right\rfloor, & \text{if } S(t_{cwe}) \leq 25 \\ 0, & \text{otherwise} \end{cases}$$

Tool Score Formula

$$\mathrm{CASTLE}(t, d^n) = \sum_{i=1}^{n} \begin{cases} 5 - (|t(d_i)| - 1) + B(t_{cwe}), & \text{if } v_i \neq \emptyset \wedge v_i \in t(d_i) \\ 2, & \text{if } v_i = \emptyset \wedge t(d_i) = \emptyset \\ -|t(d_i)|, & \text{otherwise} \end{cases}$$

Results

Theoretical maximum: 1250
No findings: 200



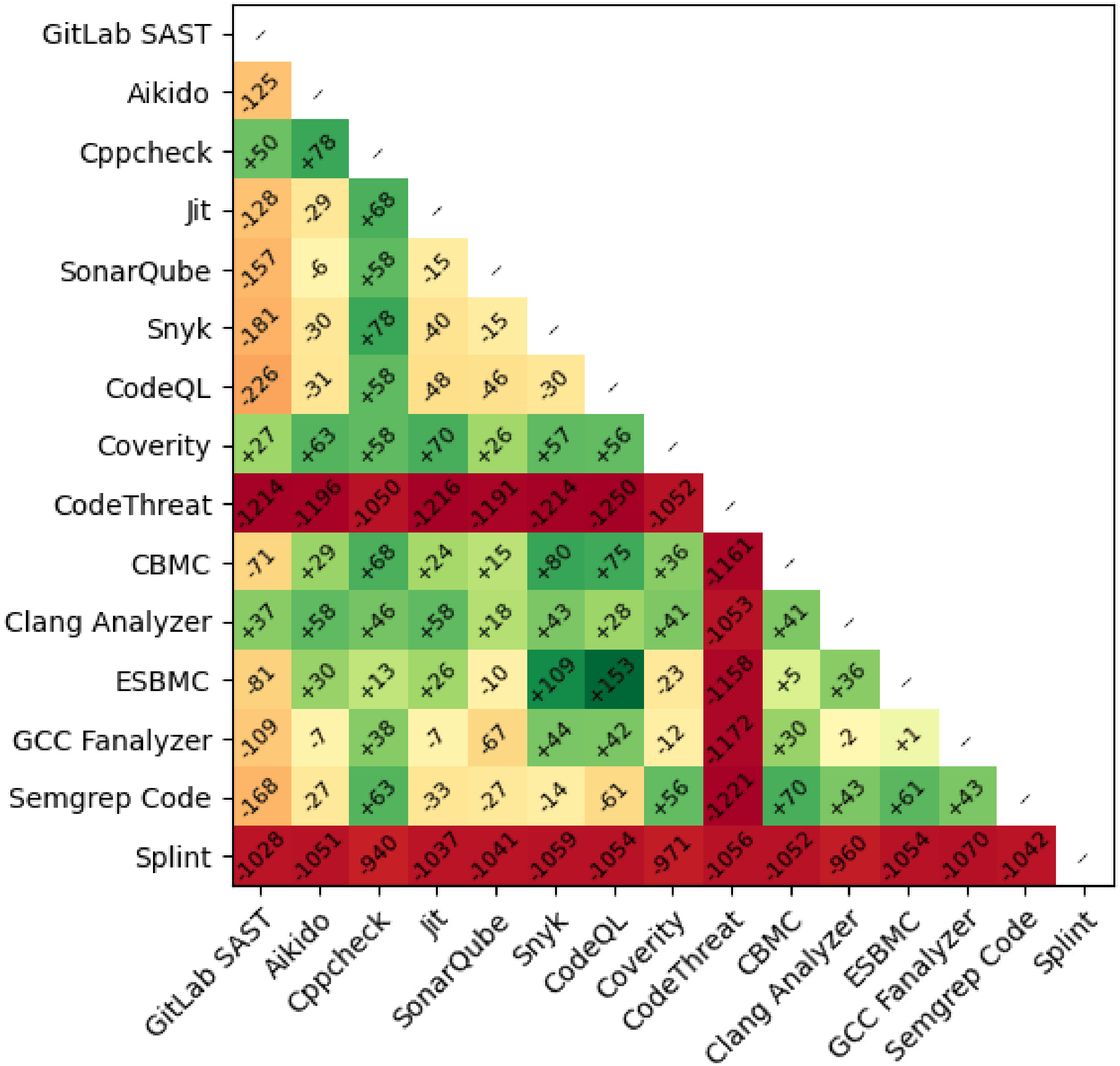
Results

TP = True Positive
TN = True Negative
FP = False Positive
FN = False Negative
P = Precision
R = Recall
A = Accuracy

* All tests were run in February 2025

		Results				Evaluation Metrics			
Name	Version	TP	TN	FP	FN	P	R	A	CASTLE Score
ESBMC	7.8.1	53	99	12	97	82%	35%	58%	697
CodeQL	2.20.1	35	84	43	115	45%	23%	43%	600
Snyk	1.1295.4	30	86	28	120	52%	20%	44%	594
CBMC	5.95.1	41	97	12	109	77%	27%	53%	547
SonarQube	25.3.0	45	73	104	105	30%	30%	36%	542
GCC Fanalyzer	13.3.0	41	81	74	109	36%	27%	40%	523
Semgrep Code	1.110.0	26	76	76	124	26%	17%	34%	486
Aikido	N/A*	12	85	31	138	28%	8%	36%	484
Coverity	2024.12.1	31	87	61	119	34%	21%	40%	428
Jit	N/A*	13	85	58	137	18%	9%	33%	427
Cppcheck	2.13.0	18	100	5	132	78%	12%	46%	405
Clang Analyzer	18.1.3	13	99	2	137	87%	9%	45%	381
GitLab SAST	15.2.1	18	67	259	132	6%	12%	18%	215
Splint	3.1.2	23	36	1029	127	2%	15%	5%	-600
CodeThreat	N/A*	21	2	1104	129	2%	14%	2%	-710
GPT-o3 Mini	-	121	61	72	29	63%	81%	64%	955
GPT-o1	-	114	66	72	36	61%	76%	62%	930
DeepSeek R1	-	133	43	163	17	45%	89%	49%	888
GPT-4o	-	113	45	141	37	44%	75%	47%	814
QWEN 2.5CI (32B)	-	106	31	226	44	32%	71%	34%	666
GPT-4o Mini	-	117	27	276	33	30%	78%	32%	663
Falcon 3 (7B)	-	36	76	70	114	34%	24%	38%	557
Mistral Ins. (7B)	-	54	23	218	96	20%	36%	20%	344
Gemma 2 (9B)	-	42	42	288	108	13%	28%	18%	301
LLAMA 3.1 (8B)	-	56	22	374	94	13%	37%	14%	245

Tool Combination Deltas



Limitations

- Microbenchmark focuses on a single vulnerability in an isolated context
- Small file size: real-world applications are longer than 42 lines
- Long-term “overfitting”: vendors may focus on specific vulnerabilities present here
- Some deviations between runs, especially for LLMs (<3%)
- This study only focuses on the C language, it is hard to generalize

Conclusion

- **LLMs** show great promise moving forward for security analysis with the best current model achieving the **highest score** of 955 points. However, they won't perform as good for larger code bases.
- **FV** methods provide the **most consistent findings** on average, but they are much more limited on the types of issues they find.
- **SAST** tools have a **high false-positive** rate, but they find most higher-level issues coming from semantic issues.
- Tool combinations can be better than a single one if chosen correcylt, out highest tested was 24% better
- The **CASTLE Score** provides a clear and comparable measure of single and combined tool performance.

Future Work

- Extend the code dataset for other common languages (Python, JavaScript, …)
- Introduce random noise with correct functions into the tests to make ”overfitting” more difficult
- Introduction of complex vulnerability chains
- Testing LLMs using RAG
- Testing LLM refining of static analyzer outputs

Thank you for your attention!

Questions?

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Repository:

https://github.com/CASTLE-Benchmark