

1

OverHAuL

2

Harnessing Automation for C Libraries via LLMs

3

Konstantinos Chousos

4

July, 2025

5 Lorem ipsum odor amet, consectetur adipiscing elit. Habitasse congue tempus erat rhoncus
6 sapien interdum dolor nec. Posuere habitant metus tellus erat eu. Risus ultricies eu rhoncus,
7 conubia euismod convallis commodo per. Nam tellus quisque maximus dui eleifend; arcu aptent.
8 Nisi rutrum primis luctus tortor tempor maecenas. Donec curae cras dolor; malesuada ultricies
9 scelerisque. Molestie class tincidunt quis gravida ut proin. Consequat lacinia arcu justo leo maecenas
10 nunc neque ex. Platea eros ullamcorper nullam rutrum facilisis.

Preface

12 Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis sagittis posuere ligula sit amet lacinia.
13 Duis dignissim pellentesque magna, rhoncus congue sapien finibus mollis. Ut eu sem laoreet,
14 vehicula ipsum in, convallis erat. Vestibulum magna sem, blandit pulvinar augue sit amet, auctor
15 malesuada sapien. Nullam faucibus leo eget eros hendrerit, non laoreet ipsum lacinia. Curabitur
16 cursus diam elit, non tempus ante volutpat a. Quisque hendrerit blandit purus non fringilla. Integer
17 sit amet elit viverra ante dapibus semper. Vestibulum viverra rutrum enim, at luctus enim posuere
18 eu. Orci varius natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus.

19 Nunc ac dignissim magna. Vestibulum vitae egestas elit. Proin feugiat leo quis ante condimentum,
20 eu ornare mauris feugiat. Pellentesque habitant morbi tristique senectus et netus et malesuada fames
21 ac turpis egestas. Mauris cursus laoreet ex, dignissim bibendum est posuere iaculis. Suspendisse
22 et maximus elit. In fringilla gravida ornare. Aenean id lectus pulvinar, sagittis felis nec, rutrum
23 risus. Nam vel neque eu arcu blandit fringilla et in quam. Aliquam luctus est sit amet vestibulum
24 eleifend. Phasellus elementum sagittis molestie. Proin tempor lorem arcu, at condimentum purus
25 volutpat eu. Fusce et pellentesque ligula. Pellentesque id tellus at erat luctus fringilla. Suspendisse
26 potenti.

27 Etiam maximus accumsan gravida. Maecenas at nunc dignissim, euismod enim ac, bibendum ipsum.
28 Maecenas vehicula velit in nisl aliquet ultricies. Nam eget massa interdum, maximus arcu vel,
29 pretium erat. Maecenas sit amet tempor purus, vitae aliquet nunc. Vivamus cursus urna velit,
30 eleifend dictum magna laoreet ut. Duis eu erat mollis, blandit magna id, tincidunt ipsum. Integer
31 massa nibh, commodo eu ex vel, venenatis efficitur ligula. Integer convallis lacus elit, maximus
32 eleifend lacus ornare ac. Vestibulum scelerisque viverra urna id lacinia. Vestibulum ante ipsum
33 primis in faucibus orci luctus et ultrices posuere cubilia curae; Aenean eget enim at diam bibendum
34 tincidunt eu non purus. Nullam id magna ultrices, sodales metus viverra, tempus turpis.

35 Acknowledgments

36 Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis sagittis posuere ligula sit amet lacinia.
37 Duis dignissim pellentesque magna, rhoncus congue sapien finibus mollis. Ut eu sem laoreet,
38 vehicula ipsum in, convallis erat. Vestibulum magna sem, blandit pulvinar augue sit amet, auctor
39 malesuada sapien. Nullam faucibus leo eget eros hendrerit, non laoreet ipsum lacinia. Curabitur
40 cursus diam elit, non tempus ante volutpat a. Quisque hendrerit blandit purus non fringilla. Integer
41 sit amet elit viverra ante dapibus semper. Vestibulum viverra rutrum enim, at luctus enim posuere
42 eu. Orci varius natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus.

Table of contents

1	Introduction	1
1.1	Motivation	1
1.2	Preview of following sections (rename)	2
2	Background	3
2.1	Fuzz Testing	3
2.1.1	Motivation	4
2.1.2	Methodology	5
2.1.3	Challenges in Adoption	7
2.2	Large Language Models (LLMs)	7
2.2.1	Biggest GPTs	8
2.2.2	Prompting	8
2.2.3	LLMs for Coding	9
2.2.4	LLMs for Fuzzing	10
2.3	Neurosymbolic AI	10
2.3.1	What is it?	10
2.3.2	What does it solve?	11
2.3.3	Its state	11
3	Related work	12
3.1	Previous Projects	12
3.1.1	KLEE	12
3.1.2	IRIS	12
3.1.3	FUDGE	13
3.1.4	UTopia	13
3.1.5	FuzzGen	13
3.1.6	OSS-Fuzz	14
3.1.7	OSS-Fuzz-Gen	14
3.1.8	AutoGen	15
3.2	Differences	15
3.2.1	IntelliGen [[20250711141156]]	16
3.2.2	CKGFuzzer [[20250711203054]]	17
3.2.3	PromptFuzz [[20250713225436]]	18
4	OverHAuL	19
4.1	Architecture	19
5	Evaluation	20
5.1	Benchmarks	20

79	5.2	Performance	20
80	5.3	Issues	20
81	5.4	Future Work	20
82	5.4.1	Technical Future Work	20
83	5.4.2	Architectural Future Work/Extensions	20
84	6	Future Work	21
85	6.1	Enhancements to Core Features	21
86	6.2	Experimentation with Large Language Models and Data Representation	22
87	6.3	Comprehensive Evaluation and Benchmarking	22
88	6.4	Practical Deployment and Community Engagement	22
89	7	Discussion	24
90	8	Conclusion	25
91		Bibliography	26

1 Introduction

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis sagittis posuere ligula sit amet lacinia. Duis dignissim pellentesque magna, rhoncus congue sapien finibus mollis. Ut eu sem laoreet, vehicula ipsum in, convallis erat. Vestibulum magna sem, blandit pulvinar augue sit amet, auctor malesuada sapien. Nullam faucibus leo eget eros hendrerit, non laoreet ipsum lacinia. Curabitur cursus diam elit, non tempus ante volutpat a. Quisque hendrerit blandit purus non fringilla. Integer sit amet elit viverra ante dapibus semper. Vestibulum viverra rutrum enim, at luctus enim posuere eu. Orci varius natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus.

Nunc ac dignissim magna. Vestibulum vitae egestas elit. Proin feugiat leo quis ante condimentum, eu ornare mauris feugiat. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris cursus laoreet ex, dignissim bibendum est posuere iaculis. Suspendisse et maximus elit. In fringilla gravida ornare. Aenean id lectus pulvinar, sagittis felis nec, rutrum risus. Nam vel neque eu arcu blandit fringilla et in quam. Aliquam luctus est sit amet vestibulum eleifend. Phasellus elementum sagittis molestie. Proin tempor lorem arcu, at condimentum purus volutpat eu. Fusce et pellentesque ligula. Pellentesque id tellus at erat luctus fringilla. Suspendisse potenti.

1.1 Motivation

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis sagittis posuere ligula sit amet lacinia. Duis dignissim pellentesque magna, rhoncus congue sapien finibus mollis. Ut eu sem laoreet, vehicula ipsum in, convallis erat. Vestibulum magna sem, blandit pulvinar augue sit amet, auctor malesuada sapien. Nullam faucibus leo eget eros hendrerit, non laoreet ipsum lacinia. Curabitur cursus diam elit, non tempus ante volutpat a. Quisque hendrerit blandit purus non fringilla. Integer sit amet elit viverra ante dapibus semper. Vestibulum viverra rutrum enim, at luctus enim posuere eu. Orci varius natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus.

Nunc ac dignissim magna. Vestibulum vitae egestas elit. Proin feugiat leo quis ante condimentum, eu ornare mauris feugiat. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris cursus laoreet ex, dignissim bibendum est posuere iaculis. Suspendisse et maximus elit. In fringilla gravida ornare. Aenean id lectus pulvinar, sagittis felis nec, rutrum risus. Nam vel neque eu arcu blandit fringilla et in quam. Aliquam luctus est sit amet vestibulum eleifend. Phasellus elementum sagittis molestie. Proin tempor lorem arcu, at condimentum purus volutpat eu. Fusce et pellentesque ligula. Pellentesque id tellus at erat luctus fringilla. Suspendisse potenti.

[1]

125 1.2 Preview of following sections (rename)

126 Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis sagittis posuere ligula sit amet lacinia.
127 Duis dignissim pellentesque magna, rhoncus congue sapien finibus mollis. Ut eu sem laoreet,
128 vehicula ipsum in, convallis erat. Vestibulum magna sem, blandit pulvinar augue sit amet, auctor
129 malesuada sapien. Nullam faucibus leo eget eros hendrerit, non laoreet ipsum lacinia. Curabitur
130 cursus diam elit, non tempus ante volutpat a. Quisque hendrerit blandit purus non fringilla. Integer
131 sit amet elit viverra ante dapibus semper. Vestibulum viverra rutrum enim, at luctus enim posuere
132 eu. Orci varius natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus.

2 Background

2.1 Fuzz Testing

Fuzzing is an automated software-testing technique in which a *Program Under Test* (PUT) is executed with (pseudo-)random inputs in the hope of exposing undefined behavior. When such behavior manifests as a crash, hang, or memory-safety violation, the corresponding input constitutes a *test-case* that reveals a bug and often a vulnerability [2]. In essence, fuzzing is a form of adversarial, penetration-style testing carried out by the defender before the adversary has an opportunity to do so. Interest in the technique surged after the publication of three practitioner-oriented books in 2007–2008 [3]–[5].

Historically, the term was coined by Miller et al. in 1990, who used “fuzz” to describe a program that “generates a stream of random characters to be consumed by a target program” [6]. This informal usage captured the essence of what fuzzing aims to do: stress test software by bombarding it with unexpected inputs to reveal bugs. To formalize this concept, we adopt Manes et al.’s rigorous definitions [2]:

Definition 2.1 (Fuzzing). Fuzzing is the execution of a Program Under Test (PUT) using input(s) sampled from an input space (the *fuzz input space*) that protrudes the expected input space of the PUT.

This means fuzzing involves running the target program on inputs that go beyond those it is typically designed to handle, aiming to uncover hidden issues. An individual instance of such execution—or a bounded sequence thereof—is called a *fuzzing run*. When these runs are conducted systematically and at scale with the specific goal of detecting violations of a security policy, the activity is known as *fuzz testing* (or simply *fuzzing*):

Definition 2.2 (Fuzz Testing). Fuzz testing is the use of fuzzing to test whether a PUT violates a security policy.

This distinction highlights that fuzz testing is fuzzing with an explicit focus on security properties and policy enforcement. Central to managing this process is the *fuzzer engine*, which orchestrates the execution of one or more fuzzing runs as part of a *fuzz campaign*. A fuzz campaign represents a concrete instance of fuzz testing tailored to a particular program and security policy:

Definition 2.3 (Fuzzer, Fuzzer Engine). A fuzzer is a program that performs fuzz testing on a PUT.

Definition 2.4 (Fuzz Campaign). A fuzz campaign is a specific execution of a fuzzer on a PUT with a specific security policy.

Throughout each execution within a campaign, a *bug oracle* plays a critical role in evaluating the program’s behavior to determine whether it violates the defined security policy:

Definition 2.5 (Bug Oracle). A bug oracle is a component (often inside the fuzzer) that determines whether a given execution of the PUT violates a specific security policy.

In practice, bug oracles often rely on runtime instrumentation techniques, such as monitoring for fatal POSIX signals (e.g., SIGSEGV) or using sanitizers like AddressSanitizer (ASan) [7]. Tools like LibFuzzer [8] commonly incorporate such instrumentation to reliably identify crashes or memory errors during fuzzing.

Most fuzz campaigns begin with a set of *seeds*—inputs that are well-formed and belong to the PUT’s expected input space—called a *seed corpus*. These seeds serve as starting points from which the fuzzer generates new test cases by applying transformations or mutations, thereby exploring a broader input space:

Definition 2.6 (Seed). An input given to the PUT that is mutated by the fuzzer to produce new test cases. During a fuzz campaign (Definition 2.4) all seeds are stored in a seed *pool* or *corpus*.

The process of selecting an effective initial corpus is crucial because it directly impacts how quickly and thoroughly the fuzzer can cover the target program’s code. This challenge—studied as the *seed-selection problem*—involves identifying seeds that enable rapid discovery of diverse execution paths and is non-trivial [9]. A well-chosen seed set often accelerates bug discovery and improves overall fuzzing efficiency.

2.1.1 Motivation

The purpose of fuzzing relies on the assumption that there are bugs within every program, which are waiting to be discovered. Therefore, a systematic approach should find them sooner or later.

— OWASP Foundation [10]

Fuzz testing offers several tangible benefits:

1. **Early vulnerability discovery:** Detecting defects during development is cheaper and safer than addressing exploits in production.
2. **Adversary-parity:** Performing the same randomised stress that attackers employ allows defenders to pre-empt zero-days.
3. **Robustness and correctness:** Beyond security, fuzzing exposes logic errors and stability issues in complex, high-throughput APIs (e.g., decompressors) even when inputs are *expected* to be well-formed.
4. **Regression prevention:** Re-running a corpus of crashing inputs as part of continuous integration ensures that fixed bugs remain fixed.

2.1.1.1 Success Stories

Heartbleed (CVE-2014-0160) [11], [12] arose from a buffer over-read¹ in OpenSSL [13] introduced on 1 February 2012 and unnoticed until 1 April 2014. Post-mortem analyses showed that a simple fuzz campaign exercising the TLS heartbeat extension would have revealed the defect almost immediately [14].

Likewise, the *Shellshock* (or *Bashdoor*) family of bugs in GNU Bash [15] enabled arbitrary command execution on many UNIX systems. While the initial flaw was fixed promptly, subsequent bug variants were discovered by Google’s Michał Zalewski using his own fuzzer [16] in late 2014 [17].

On the defensive tooling side, the security tool named *Mayhem*—developed by the company of the same name—has since been adopted by the US Air Force, the Pentagon, Cloudflare, and numerous open-source communities. It has found and facilitated the remediation of thousands of previously unknown vulnerabilities [18].

These cases underscore the central thesis of fuzz testing: exhaustive manual review is infeasible, but scalable stochastic exploration reliably surfaces the critical few defects that matter most.

2.1.2 Methodology

As previously discussed, fuzz testing of a program under test (PUT) is typically conducted using a dedicated fuzzing engine (see Definition 2.3). Among the most widely adopted fuzzers for C and C++ projects and libraries are AFL [16]—which has since evolved into AFL++ [19]—and LibFuzzer [8]. Within the OverHAuL framework, LibFuzzer is preferred owing to its superior suitability for library fuzzing, whereas AFL++ predominantly targets executables and binary fuzzing.

2.1.2.1 LibFuzzer

LibFuzzer [8] is an in-process, coverage-guided evolutionary fuzzing engine primarily designed for testing libraries. It forms part of the LLVM ecosystem [20] and operates by linking directly with the library under evaluation. The fuzzer delivers mutated input data to the library through a designated fuzzing entry point, commonly referred to as the *fuzz target*.

Definition 2.7 (Fuzz target). A function that accepts a byte array as input and exercises the application programming interface (API) under test using these inputs [8]. This construct is also known as a *fuzz driver*, *fuzzer entry point*, or *fuzzing harness*.

For the remainder of this thesis, the terms presented in Definition 2.7 will be used interchangeably.

To effectively validate an implementation or library, developers are required to author a fuzzing harness that invokes the target library’s API functions utilizing the fuzz-generated inputs. This harness serves as the principal interface for the fuzzer and is executed iteratively, each time with mutated input designed to maximize code coverage and uncover defects. To comply with LibFuzzer’s interface requirements, a harness must conform to the following function signature:

¹<https://xkcd.com/1354/>

Listing 2.1 This function receives the fuzzing input via a pointer to an array of bytes (*Data*) and its associated size (*Size*). Efficiency in fuzzing is achieved by invoking the API of interest within the body of this function, thereby allowing the fuzzer to explore a broad spectrum of behavior through systematic input mutation.

```
1 int LLVMFuzzerTestOneInput(const uint8_t *Data, size_t Size) {  
2     DoSomethingInterestingWithData(Data, Size);  
3     return 0;  
4 }
```

232 A more illustrative example of such a harness is provided in Listing 2.2.

Listing 2.2 This example demonstrates a minimal harness that triggers a controlled crash upon receiving *HI!* as input.

```
1 // test_fuzzer.cpp  
2 #include <stdint.h>  
3 #include <stddef.h>  
4  
5 extern "C" int LLVMFuzzerTestOneInput(const uint8_t *data, size_t size) {  
6     if (size > 0 && data[0] == 'H')  
7         if (size > 1 && data[1] == 'I')  
8             if (size > 2 && data[2] == '!')  
9                 __builtin_trap();  
10    return 0;  
11 }
```

233 To compile and link such a harness with LibFuzzer, the Clang compiler—also part of the LLVM
234 project [20]—must be used alongside appropriate compiler flags. For instance, compiling the harness
235 in Listing 2.2 can be achieved as follows:

236 2.1.2.2 AFL and AFL++

237 *American Fuzzy Lop* (AFL) [16], developed by Michał Zalewski, is a seminal fuzzer targeting C and
238 C++ applications. Its core methodology relies on instrumented binaries to provide edge coverage
239 feedback, thereby guiding input mutation towards unexplored program paths. AFL supports several
240 emulation backends including QEMU [21]—an open-source CPU emulator facilitating fuzzing on
241 diverse architectures—and Unicorn [22], a lightweight multi-platform CPU emulator. While AFL
242 established itself as a foundational tool within the fuzzing community, its successor AFL++ [19]
243 incorporates numerous enhancements and additional features to improve fuzzing efficacy.

244 AFL operates by ingesting seed inputs from a specified directory (*seeds_dir*), applying mutations,
245 and then executing the target binary to discover novel execution paths. Execution can be initiated
246 using the following command-line syntax:

Listing 2.3 This example illustrates the compilation and execution workflow necessary for deploying a LibFuzzer-based fuzzing harness.

```
1 # Compile test_fuzzer.cc with AddressSanitizer and link against LibFuzzer.
2 clang++ -fsanitize=address,fuzzer test_fuzzer.cc
3 # Execute the fuzzer without any pre-existing seed corpus.
4 ./a.out
```

```
1 ./afl-fuzz -i seeds_dir -o output_dir -- /path/to/tested/program
```

247 AFL is capable of fuzzing both black-box and instrumented binaries, employing a fork-server
248 mechanism to optimize performance. It additionally supports persistent mode execution as well
249 as modes leveraging QEMU and Unicorn emulators, thereby providing extensive flexibility for
250 different testing environments.

251 Although AFL is traditionally utilized for fuzzing standalone programs or binaries, it is also capable
252 of fuzzing libraries and other software components. In such scenarios, rather than implementing
253 the LLVMFuzzerTestOneInput style harness, AFL can use the standard main() function as the fuzzing
254 entry point. Nonetheless, AFL also accommodates integration with LLVMFuzzerTestOneInput-based
255 harnesses, underscoring its adaptability across varied fuzzing use cases.

256 2.1.3 Challenges in Adoption

257 Despite its potential for uncovering software vulnerabilities, fuzzing remains a relatively underuti-
258 lized testing technique compared to more established methodologies such as Test-Driven Develop-
259 ment (TDD). This limited adoption can be attributed, in part, to the substantial initial investment
260 required to design and implement appropriate test harnesses that enable effective fuzzing processes.
261 Furthermore, the interpretation of fuzzing outcomes—particularly the identification, diagnostic
262 analysis, and prioritization of program crashes—demands considerable resources and specialized
263 expertise. These factors collectively pose significant barriers to the widespread integration of
264 fuzzing within standard software development and testing practices.

265 2.2 Large Language Models (LLMs)

266 Natural Language Processing (NLP), a subfield of Artificial Intelligence (AI), has a rich and ongoing
267 history that has evolved significantly since its beginning in the 1990s [23], [24]. Among the most
268 notable—and recent—advancements in this domain are Large Language Models (LLMs), which have
269 transformed the landscape of NLP and AI in general.

270 At the core of many LLMs is the attention mechanism, which was introduced by Bahdanau et
271 al. in 2014 [25]. This pivotal innovation enabled models to focus on relevant parts of the input
272 sequence when making predictions, significantly improving language understanding and generation

tasks. Building on this foundation, the Transformer architecture was proposed by Vaswani et al. in 2017 [26]. This architecture has become the backbone of most contemporary LLMs, as it efficiently processes sequences of data, capturing long-range dependencies without being hindered by sequential processing limitations.

One of the first major breakthroughs utilizing the Transformer architecture was BERT (Bidirectional Encoder Representations from Transformers), developed by Devlin et al. in 2019 [27]. BERT’s bi-directional understanding allowed it to capture the context of words from both directions, which improved the accuracy of various NLP tasks. Following this, the Generative Pre-trained Transformer (GPT) series, initiated by OpenAI with the original GPT model in 2018 [28], further pushed the boundaries. Subsequent iterations, including GPT-2 [29], GPT-3 [30], and the most current GPT-4 [31], have continued to enhance performance by scaling model size, data, and training techniques.

In addition to OpenAI’s contributions, other significant models have emerged, such as Claude, DeepSeek-R1 and the Llama series (1 through 3) [32]–[34]. The proliferation of LLMs has sparked an active discourse about their capabilities, applications, and implications in various fields.

2.2.1 Biggest GPTs

User-facing LLMs are generally categorized between closed-source and open-source models. Closed-source LLMs like ChatGPT, Claude, and Gemini [32], [35], [36] represent commercially developed systems often optimized for specific tasks without public access to their underlying weights. In contrast, open-source models², including the Llama series [34] and Deepseek [33], provide researchers and practitioners with access to model weights, allowing for greater transparency and adaptability.

2.2.2 Prompting

Interaction with LLMs typically occurs through chat-like interfaces, a process commonly referred to as *prompting*. A critical aspect of effective engagement with LLMs is the usage of different prompting strategies, which can significantly influence the quality and relevance of the generated outputs. Various approaches to prompting have been developed and studied, including zero-shot and few-shot prompting. In zero-shot prompting, the model is expected to perform a specific task without any examples, while in few-shot prompting, the user provides a limited number of examples to guide the model’s responses [30].

To enhance performance on more complex tasks, several advanced prompting techniques have emerged. One notable strategy is the *Chain of Thought* approach [37], which entails presenting the model with sample thought processes for solving a given task. This method encourages the model to generate more coherent and logical reasoning by mimicking human-like cognitive pathways. A refined variant of this approach is the *Tree of Thoughts* technique [38], which enables the LLM

²The term “open-source” models is somewhat misleading, since these are better termed as *open-weights* models. While their weights are publicly available, their training data and underlying code are often proprietary. This terminology reflects community usage but fails to capture the limitations of transparency and accessibility inherent in these models.

to explore multiple lines of reasoning concurrently, thereby facilitating the selection of the most promising train of thought for further exploration.

In addition to these cognitive strategies, Retrieval-Augmented Generation (RAG) [39] is another innovative technique that enhances the model’s capacity to provide accurate information by incorporating external knowledge not present in its training dataset. RAG operates by integrating the LLM with an external storage system—often a vector store containing relevant documents—that the model can query in real-time. This allows the LLM to pull up pertinent and/or proprietary information in response to user queries, resulting in more comprehensive and accurate answers.

Moreover, the ReAct framework [40], which stands for Reasoning and Acting, empowers LLMs by granting access to external tools. This capability allows LLM instances to function as intelligent agents that can interact meaningfully with their environment through user-defined tools. For instance, a ReAct tool could be a function that returns a weather forecast based on the user’s current location. In this scenario, the LLM can provide accurate and truthful predictions, thereby mitigating risks associated with hallucinated responses.

2.2.3 LLMs for Coding

The impact of LLMs in software development in recent years is apparent, with hundreds of LLM-assistance extensions and Integrated Development Environments (IDEs) being published. Notable instances include tools like GitHub Copilot and IDEs such as Cursor, which leverage LLM capabilities to provide developers with coding suggestions, auto-completions, and even real-time debugging assistance [41], [42]. Such innovations have introduced a layer of interaction that enhances productivity and fosters a more intuitive coding experience. Simultaneously, certain LLMs are trained themselves with the code-generation task in mind [43]–[45].

One exemplary product of this innovation is *vibecoding* and the no-code movement, which describe the development of software by only prompting and tasking an LLM, i.e. without any actual programming required by the user. This constitutes a showcase of how LLMs can be harnessed to elevate the coding experience by supporting developers as they navigate complex programming tasks [46]. By analyzing the context of the code being written, these sophisticated models can provide contextualized insights and relevant snippets, effectively streamlining the development process. Developers can benefit from reduced cognitive load, as they receive suggestions that not only cater to immediate coding needs but also promote adherence to best practices and coding standards.

Despite these advancements, it is crucial to recognize the inherent limitations of LLMs when applied to software development. While they can help in many aspects of coding, they are not immune to generating erroneous outputs—a phenomenon often referred to as “hallucination”. Hallucinations occur when LLMs produce information that is unfounded or inaccurate, which can stem from several factors, including the limitations of their training data and the constrained context window within which they operate. As LLMs generate code suggestions based on the patterns learned from vast datasets, they may inadvertently propose solutions that do not align with the specific requirements of a task or that utilize outdated programming paradigms.

Moreover, the challenge of limited context windows can lead to suboptimal suggestions. LLMs generally process a fixed amount of text when generating responses, which can impact their ability to fully grasp the nuances of complex coding scenarios. This may result in outputs that lack the necessary depth and specificity required for successful implementation. As a consequence, developers must exercise caution and critically evaluate the suggestions offered by these models, as reliance on them without due diligence could lead to the introduction of bugs or other issues in the code.

2.2.4 LLMs for Fuzzing

While large language models (LLMs) demonstrate significant potential in enhancing the software development process, the challenges highlighted in Section 2.2.3 become even more pronounced and troublesome when these models are employed to generate fuzzing harnesses. The task of writing a fuzzing harness inherently demands an in-depth comprehension of both the library being tested and the intricate interactions expected among its various components. This level of understanding is often beyond the capabilities of LLMs, primarily due to their context window limitations, which restrict the amount of information they can effectively process and retain during code generation.

In addition to this issue, the risk of error-prone code produced by LLMs further complicates the fuzzing workflow. When a crash occurs during the fuzzing process, it becomes imperative for developers to ascertain that the root cause of the failure is not attributable to deficiencies or bugs within the harness itself. This additional layer of verification adds to the cognitive load placed upon developers, potentially detracting from their ability to focus on testing and improving the underlying software.

To enhance the reliability of LLM-generated harnesses in fuzzing contexts, it is essential that these generated artifacts undergo thorough evaluation and validation through programmatic means. This involves the implementation of systematic techniques that assess the accuracy and robustness of the generated code, ensuring that it aligns with the expected behavior of the components it is intended to interact with. This strategy can be conceptualized within the framework of Neurosymbolic AI, which seeks to integrate the strengths of neural networks with symbolic reasoning capabilities. By marrying these two paradigms, it may be possible to improve the reliability and efficacy of LLMs in the creation of fuzzing harnesses, ultimately leading to a more seamless integration of automated testing methodologies into the software development lifecycle.

2.3 Neurosymbolic AI

qqqq

TODO [47]–[52].

2.3.1 What is it?

[49], [51] Neurosymbolic AI for attribution in LLMs [52]

381 **2.3.2 What does it solve?**

382 **2.3.3 Its state**

383 restatement of overarching goal, segue to section 2

3 Related work

Automated testing, automated fuzzing and automated harness creation have a long research history. Still, a lot of ground remains to be covered until true automation of these tasks is achieved. Until the introduction of transformers [26] and the 2020’s boom of commercial GPTs [35], automation regarding testing and fuzzing was mainly attempted through static and dynamic program analysis methods. These approaches are still utilized, but the fuzzing community has shifted almost entirely to researching the incorporation and employment of LLMs in the last half decade, in the name of automation [53]–[62].

3.1 Previous Projects

3.1.1 KLEE

KLEE [63] is a seminal and widely cited symbolic execution engine introduced in 2008 by Cadar et al. It was designed to automatically generate high-coverage test cases for programs written in C, using symbolic execution to systematically explore the control flow of a program. KLEE operates on the LLVM [20] bytecode representation of programs, allowing it to be applied to a wide range of C programs compiled to the LLVM intermediate representation.

Instead of executing a program on concrete inputs, KLEE performs symbolic execution—that is, it runs the program on symbolic inputs, which represent all possible values simultaneously. At each conditional branch, KLEE explores both paths by forking the execution and accumulating path constraints (i.e., logical conditions on input variables) along each path. This enables it to traverse many feasible execution paths in the program, including corner cases that may be difficult to reach through random testing or manual test creation.

When an execution path reaches a terminal state (e.g., a program exit, an assertion failure, or a segmentation fault), KLEE uses a constraint solver to compute concrete input values that satisfy the accumulated constraints for that path. These values form a test case that will deterministically drive the program down that specific path when executed concretely.

3.1.2 IRIS

IRIS [53] is a 2025 open-source neurosymbolic system for static vulnerability analysis. Given a codebase and a list of user-specified Common Weakness Enumerations (CWEs), it analyzes source code to identify paths that may correspond to known vulnerability classes. IRIS combines symbolic analysis—such as control- and data-flow reasoning—with neural models trained to generalize over

code patterns. It outputs candidate vulnerable paths along with explanations and CWE references. The system operates on full repositories and supports extensible CWE definitions.

3.1.3 FUDGE

FUDGE [62] is a closed-source tool, made by Google, for automatic harness generation of C and C++ projects based on existing client code. It was used in conjunction with and in the improvement of Google’s OSS-Fuzz [64]. Being deployed inside Google’s infrastructure, FUDGE continuously examines Google’s internal code repository, searching for code that uses external libraries in a meaningful and “fuzzable” way (i.e. predominantly for parsing). If found, such code is **sliced** [65], per FUDGE, based on its Abstract Syntax Tree (AST) using LLVM’s Clang tool [20]. The above process results in a set of abstracted mostly-self-contained code snippets that make use of a library’s calls and/or API. These snippets are later **synthesized** into the body of a fuzz driver, with variables being replaced and the fuzz input being utilized. Each is then injected in an LLVMFuzzerTestOneInput function and finalized as a fuzzing harness. A building and evaluation phase follows for each harness, where they are executed and examined. Every passing harness along with its evaluation results is stored in FUDGE’s database, reachable to the user through a custom web-based UI.

3.1.4 UTopia

UTopia [58] (stylized UTOPIA) is another open-source automatic harness generation framework. Aside from the library code, It operates solely on user-provided unit tests since, according to Jeong, Jang, Yi, *et al.* [58], they are a resource of complete and correct API usage examples containing working library set-ups and tear-downs. Additionally, each of them are already close to a fuzz target, in the sense that they already examine a single and self-contained API usage pattern. Each generated harness follows the same data flow of the originating unit test. Static analysis is employed to figure out what fuzz input placement would yield the most results. It is also utilized in abstracting the tests away from the syntactical differences between testing frameworks, along with slicing and AST traversing using Clang.

3.1.5 FuzzGen

Another project of Google is FuzzGen [61], this time open-source. Like FUDGE, it leverages existing client code of the target library to create fuzz targets for it. FuzzGen uses whole-system analysis, through which it creates an *Abstract API Dependence Graph* (A^2DG). It uses the latter to automatically generate LibFuzzer-compatible harnesses. For FuzzGen to work, the user needs to provide both client code and/or tests for the API and the API library’s source code as well. FuzzGen uses the client code to infer the *correct usage* of the API and not its general structure, in contrast to FUDGE. FuzzGen’s workflow can be divided into three phases: **1. API usage inference.** By consuming and analyzing client code and tests that concern the library under test, FuzzGen recognizes which functions belong to the library and learns its correct API usage patterns. This process is done with the help of Clang. To test if a function is actually a part of the library, a sample program is created that uses it. If the program compiles successfully, then the function is indeed a valid API call. **2. A^2DG construction mechanism.** For all the existing API calls, FuzzGen

452 builds an A²DG to record the API usages and infers its intended structure. After completion, this
453 directed graph contains all the valid API call sequences found in the client code corpus. It is built
454 in a two-step process: First, many smaller A²DGs are created, one for each root function per client
455 code snippet. Once such graphs have been created for all the available client code instances, they
456 are combined to formulate the master A²DG. This graph can be seen as a template for correct usage
457 of the library. **3. Fuzzer generator.** Through the A²DG, a fuzzing harness is created. Contrary to
458 FUDGE, FuzzGen does not create multiple “simple” harnesses but a single complex one with the
459 goal of covering the whole of the A²DG. In other words, while FUDGE fuzzes a single API call at a
460 time, FuzzGen’s result is a single harness that tries to fuzz the given library all at once through
461 complex API usage.

462 3.1.6 OSS-Fuzz

463 OSS-Fuzz [64], [66] is a continuous, scalable and distributed cloud fuzzing solution for critical
464 and prominent open-source projects. Developers of such software can submit their projects to
465 OSS-Fuzz’s platform, where its harnesses are built and constantly executed. This results in multiple
466 bug findings that are later disclosed to the primary developers and are later patched.

467 OSS-Fuzz started operating in 2016, an initiative in response to the Heartbleed vulnerability [11],
468 [12], [14]. Its hope is that through more extensive fuzzing such errors could be caught and corrected
469 before having the chance to be exploited and thus disrupt the public digital infrastructure. So far,
470 it has helped uncover over 10,000 security vulnerabilities and 36,000 bugs across more than 1,000
471 projects, significantly enhancing the quality and security of major software like Chrome, OpenSSL,
472 and systemd.

473 A project that’s part of OSS-Fuzz must have been configured as a ClusterFuzz [67] project. Cluster-
474 Fuzz is the fuzzing infrastructure that OSS-Fuzz uses under the hood and depends on Google Cloud
475 Platform services, although it can be hosted locally. Such an integration requires setting up a build
476 pipeline, fuzzing jobs and expects a Google Developer account. Results are accessible through a
477 web interface. ClusterFuzz, and by extension OSS-Fuzz, supports fuzzing through LibFuzzer, AFL++,
478 Honggfuzz and FuzzTest—successor to Centipede— with the last two being Google projects [8],
479 [19], [68], [69]. C, C++, Rust, Go, Python and Java/JVM projects are supported.

480 3.1.7 OSS-Fuzz-Gen

481 OSS-Fuzz-Gen (OFG) [56], [70] is Google’s current State-Of-The-Art (SOTA) project regarding
482 automatic harness generation through LLMs. It’s purpose is to improve the fuzzing infrastructure of
483 open-source projects that are already integrated into OSS-Fuzz. Given such a project, OSS-Fuzz-Gen
484 uses its preexisting fuzzing harnesses and modifies them to produce new ones. Its architecture
485 can be described as follows: 1. With an OSS-Fuzz project’s GitHub repository link, OSS-Fuzz-
486 Gen iterates through a set of predefined build templates and generates potential build scripts
487 for the project’s harnesses. 2. If any of them succeed they are once again compiled, this time
488 through fuzz-introspector [71]. The latter constitutes a static analysis tool, with fuzzer developers
489 specifically in mind. 3. Build results, old harness and fuzz-introspector report are included in a
490 template-generated prompt, through which an LLM is called to generate a new harness. 4. The

newly generated fuzz target is compiled and if it is done so successfully it begins execution inside OSS-Fuzz’s infrastructure.

This method proved meaningful, with code coverage in fuzz campaigns increasing thanks to the new generated fuzz drivers. In the case of [72], line coverage went from 38% to 69% without any manual interventions [70].

In 2024, OSS-Fuzz-Gen introduced an experimental feature for generating harnesses in previously unfuzzed projects [73]. The code for this feature resides in the `experimental/from_scratch` directory of the project’s GitHub repository [56], with the latest known working commit being 171aac2 and the latest overall commit being four months ago.

3.1.8 AutoGen

AutoGen [54] is a closed-source tool that generates new fuzzing harnesses, given only the library code and documentation. It works as following: The user specifies the function for which a harness is to be generated. AutoGen gathers information for this function—such as the function body, used header files, function calling examples—from the source code and documentation. Through specific prompt templates containing the above information, an LLM is tasked with generating a new fuzz driver, while another is tasked with generating a compilation command for said driver. If the compilation fails, both LLMs are called again to fix the problem, whether it was on the driver’s or command’s side. This loop iterates until a predefined maximum value or until a fuzz driver is successfully generated and compiled. If the latter is the case, it is then executed. If execution errors exist, the LLM responsible for the driver generation is used to correct them. If not, the pipeline has terminated and a new fuzz driver has been successfully generated.

3.2 Differences

OverHAuL differs, in some way, with each of the aforementioned works. Firstly, although KLEE and IRIS [53], [63] tackle the problem of automated testing and both IRIS and OverHAuL can be considered neurosymbolic AI tools, the similarities end there. None of them utilize LLMs the same way we do—with KLEE not utilizing them by default, as it precedes them chronologically—and neither are automating any part of the fuzzing process.

When it comes to FUDGE, FuzzGen and UTopia [58], [61], [62], all three depend on and demand existing client code and/or unit tests. On the other hand, OverHAuL requires only the bare minimum: the library code itself. Another point of difference is that in contrast with OverHAuL, these tools operate in a linear fashion. No feedback is produced or used in any step and any point failure results in the termination of the entire run.

OverHAuL challenges a common principle of these tools, stated explicitly in FUDGE’s paper [62]: “Choosing a suitable fuzz target (still) requires a human”. OverHAuL chooses to let the LLM, instead of the user, explore the available functions and choose one to target in its fuzz driver.

OSS-Fuzz-Gen [56] can be considered a close counterpart of OverHAuL, and in some ways it is. A lot of inspiration was gathered from it, like for example the inclusion of static analysis and its

usage in informing the LLM. Yet, OSS-Fuzz-Gen has a number of disadvantages that make it in some cases an inferior option. For one, OFG is tightly coupled with the OSS-Fuzz platform [64], which even on its own creates a plethora of issues for the common developer. To integrate their project into OSS-Fuzz, they would need to: Transform it into a ClusterFuzz project [67] and take time to write harnesses for it. Even if these prerequisites are carried out, it probably would not be enough. Per OSS-Fuzz’s documentation [66]: “To be accepted to OSS-Fuzz, an open-source project must have a significant user base and/or be critical to the global IT infrastructure”. This means that OSS-Fuzz is a viable option only for a small minority of open-source developers and maintainers. One countermeasure of the above shortcoming would be for a developer to run OSS-Fuzz-Gen locally. This unfortunately proves to be an arduous task. As it is not meant to be used standalone, OFG is not packaged in the form of a self-contained application. This makes it hard to setup and difficult to use interactively. Like in the case of FUDGE, OFG’s actions are performed linearly. No feedback is utilized nor is there graceful error handling in the case of a step’s failure. Even in the case of the experimental feature for bootstrapping unfuzzed projects, OFG’s performance varies heavily. During experimentation, a lot of generated harnesses were still wrapped either in Markdown backticks or `tags, or were accompanied with explanations inside the generated .c source file. Even if code was formatted correctly, in many cases it missed necessary headers for compilation or used undeclared functions.`

Lastly, the closest counterpart to OverHAuL is AutoGen [54]. Their similarity stands in the implementation of a feedback loop between LLM and generated harness. However, most other implementation decisions remain distinct. One difference regards the fuzzed function. While AutoGen requires a target function to be specified by the user in which it narrows during its whole run, OverHAuL delegates this to the LLM, letting it explore the codebase and decide by itself the best candidate. Another difference lies in the need—and the lack of—of documentation. While AutoGen requires it to gather information for the given function, OverHAuL leans into the role of a developer by reading the related code and comments and thus avoiding any mismatches between documentation and code. Finally, the LLMs’ input is built based on predefined prompt templates, a technique also present in OSS-Fuzz-Gen. OverHAuL operates one abstraction level higher, leveraging DSPy [74] for programming instead of prompting the LLMs used.

In conclusion, OverHAuL constitutes an *open-source* tool that offers new functionality by offering a straightforward installation process, packaged as a self-contained Python package with minimal external dependencies. It also introduces novel approaches compared to previous work by

1. Implementing a feedback mechanism between harness generation, compilation, and evaluation phases,
2. Using autonomous ReAct agents capable of codebase exploration,
3. Leveraging a vector store for code consumption and retrieval.

TODO να συμπεριλάβω και τα:

3.2.1 IntelliGen [[20250711141156]]

SAMPLE

IntelliGen: Automatic Fuzz Driver Synthesis Based on Vulnerability Heuristics Zhang et al. (2021) present **IntelliGen**, a system for automatically synthesizing fuzz drivers by statically identifying potentially vulnerable entry-point functions within C projects. Implemented using LLVM, IntelliGen focuses on improving fuzzing efficiency by targeting code more likely to contain memory safety issues, rather than exhaustively fuzzing all available functions.

The system comprises two main components: the **Entry Function Locator** and the **Fuzz Driver Synthesizer**. The Entry Function Locator analyzes the project’s abstract syntax tree (AST) and classifies functions based on heuristics that indicate vulnerability. These include pointer dereferencing, calls to memory-related functions (e.g., `memcpy`, `memset`), and invocation of other internal functions. Functions that score highly on these metrics are prioritized for fuzz driver generation. The guiding insight is that entry points with fewer argument checks and more direct memory operations expose more useful program logic for fuzz testing.

The Fuzz Driver Synthesizer then generates harnesses for these entry points. For each target function, it synthesizes a `LLVMFuzzerTestOneInput` function that invokes the target with arguments derived from the fuzzer input. This process involves inferring argument types from the source code and ensuring that runtime behavior does not violate memory safety—thus avoiding invalid inputs that would cause crashes unrelated to genuine bugs.

IntelliGen stands out by integrating static vulnerability estimation into the driver generation pipeline. Compared to prior tools like FuzzGen and FUDGE, it uses a more targeted, heuristic-based selection of functions, increasing the likelihood that fuzzing will exercise meaningful and vulnerable code paths.

3.2.2 CKGFuzzer [[20250711203054]]

SAMPLE

CKGFuzzer is a fuzzing framework designed to automate the generation of effective fuzz drivers for C/C++ libraries by leveraging static analysis and large language models. Its workflow begins by parsing the target project along with any associated library APIs to construct a code knowledge graph. This involves two primary steps: first, parsing the abstract syntax tree (AST), and second, performing interprocedural program analysis. Through this process, CKGFuzzer extracts essential program elements such as data structures, function signatures, function implementations, and call relationships.

Using the knowledge graph, CKGFuzzer then identifies and queries meaningful API combinations, focusing on those that are either frequently invoked together or exhibit functional similarity. It generates candidate fuzz drivers for these combinations and attempts to compile them. Any compilation errors encountered during this phase are automatically repaired using heuristics and domain knowledge. A dynamically updated knowledge base, constructed from prior library usage patterns, guides both the generation and repair processes.

Once the drivers are successfully compiled, CKGFuzzer executes them while monitoring code coverage at the file level. It uses coverage feedback to iteratively mutate underperforming API combinations, refining them until new execution paths are discovered or a preset mutation budget is exhausted.

607 Finally, any crashes triggered during fuzzing are subjected to a reasoning process based on chain-
608 of-thought prompting. To help determine their severity and root cause, CKGFuzzer consults an
609 LLM-generated knowledge base containing real-world examples of vulnerabilities mapped to known
610 Common Weakness Enumeration (CWE) entries.

611 3.2.3 PromptFuzz [[20250713225436]]

612 SAMPLE

613 Lyu et al. (2024) introduce PromptFuzz [75], a system for automatically generating fuzz drivers using
614 LLMs, with a novel focus on **prompt mutation** to improve coverage. The system is implemented
615 in Rust and targets C libraries, aiming to explore more of the API surface with each iteration.

616 The workflow begins with the random selection of API functions, extracted from header file
617 declarations. These functions are used to construct initial prompts that instruct the LLM to generate
618 a simple program utilizing the API. Each generated program is compiled, executed, and monitored
619 for code coverage. Programs that fail to compile or violate runtime checks (e.g., sanitizers) are
620 discarded.

621 A key innovation in PromptFuzz is **coverage-guided prompt mutation**. Instead of mutating
622 generated code directly, PromptFuzz mutates the LLM prompts—selecting new combinations of API
623 functions to target unexplored code paths. This process is guided by a **power scheduling** strategy
624 that prioritizes underused or promising API functions based on feedback from previous runs.

625 Once an effective program is produced, it is transformed into a fuzz driver by replacing constants
626 and arguments with variables derived from the fuzzer input. Multiple such drivers are embedded
627 into a single harness, where the input determines which program variant to execute, typically via a
628 case-switch construct.

629 Overall, PromptFuzz demonstrates that prompt-level mutation enables more effective exploration
630 of complex APIs and achieves better coverage than direct code mutations, offering a compelling
631 direction for LLM-based automated fuzzing systems.

632 4 OverHAuL

- 633 1. How is it different?
- 634 2. What does it offer?
- 635 3. Example uses
- 636 4. Scope of Usage
 - 637 1. In what contexts does it work?
 - 638 2. Prerequisites

639 4.1 Architecture

- 640 • System diagram
- 641 • Main Library Architecture/Structure
- 642 • LLM usage
 - 643 – Prompting techniques used (callback to Section 2.2.2).
- 644 • Static analysis
- 645 • Code localization(?)
- 646 • Fuzzers
- 647 • GitHub Workflow/Usage
- 648 • “Iteration budget”
- 649 • LLM Programming Libraries (?) Langchain & LangGraph, LlamaIndex [76]–[78]. DSPy [74].
- 650 Comparison, relevance to our usecase.

651 5 Evaluation

652 5.1 Benchmarks

653 Results from integration with 10/100 open-source C/C++ projects.

654 5.2 Performance

655 5.3 Issues

656 5.4 Future Work

657 5.4.1 Technical Future Work

658 5.4.2 Architectural Future Work/Extensions

- 659 1. Build system
- 660 2. More (static) analysis tools integrations
- 661 3. General *localization* problem

6 Future Work

The prototype implementation of OverHAuL offers a compelling demonstration of its potential to automate the fuzzing process for open-source libraries, providing tangible benefits to developers and maintainers alike. This initial version successfully validates the core design principles underpinning OverHAuL, showcasing its ability to streamline and enhance the software testing workflow through automated generation of fuzz drivers using large language models. Nevertheless, while these foundational capabilities lay a solid groundwork, numerous avenues exist for further expansion, refinement, and rigorous evaluation to fully realize the tool’s potential and adapt to evolving challenges in software quality assurance.

6.1 Enhancements to Core Features

Enhancing OverHAuL’s core functionality represents a primary direction for future development. First, expanding support to encompass a wider array of build systems commonly employed in C and C++ projects—such as GNU Make, CMake, Meson, and Ninja [79]–[82]—would significantly broaden the scope of libraries amenable to automated fuzzing using OverHAuL. This advancement would enable OverHAuL to scale effectively and be applied to larger, more complex codebases, thereby increasing its practical utility and impact.

Second, integrating additional fuzzing engines beyond LibFuzzer stands out as a strategic enhancement. Incorporation of widely adopted fuzzers like AFL++ [19] could diversify the fuzzing strategies available to OverHAuL, while exploring more experimental tools such as GraphFuzz [57] may pioneer specialized approaches for certain code patterns or architectures. Multi-engine support would also facilitate extending language coverage, for instance by incorporating fuzzers tailored to other programming ecosystems—for example, Google’s Atheris for Python projects [83]. Such versatility would position OverHAuL as a more universal fuzzing automation platform.

Third, the evaluation component of OverHAuL presents an opportunity for refinement through more sophisticated analysis techniques. Beyond the current criteria, incorporating dynamic metrics such as differential code coverage tracking between generated fuzz harnesses would yield deeper insights into test quality and coverage completeness. This quantitative evaluation could guide iterative improvements in fuzz driver generation and overall testing effectiveness.

Finally, OverHAuL’s methodology could be extended to leverage existing client codebases and unit tests in addition to the library source code itself, resources that for now OverHAuL leaves untapped. Inspired by approaches like those found in FUDGE and FuzzGen [61], [62], this enhancement would enable the tool to exploit programmer-written usage scenarios as seeds or contexts, potentially generating more meaningful and targeted fuzz inputs. Incorporating these richer information sources would likely improve the efficacy of fuzzing campaigns and uncover subtler bugs.

6.2 Experimentation with Large Language Models and Data Representation

OverHAuL’s reliance on large language models (LLMs) invites comprehensive experimentation with different providers and architectures to assess their comparative strengths and limitations. Conducting empirical evaluations across leading models—such as OpenAI’s o1 and o3 families and Anthropic’s Claude Opus 4—will provide valuable insights into their capabilities, cost-efficiency, and suitability for fuzz driver synthesis. Additionally, specialized code-focused LLMs, including generative and fill-in models like Codex-1 and CodeGen [43]–[45], merit exploration due to their targeted optimization for source code generation and understanding.

Another dimension worthy of investigation concerns the granularity of code chunking employed during the given project’s code processing stage. Whereas the current approach partitions code at the function level, experimenting with more nuanced segmentation strategies—such as splitting per step inside a function, as a finer-grained technique—could improve the semantic coherence of stored representations and enhance retrieval relevance during fuzz driver generation. This line of inquiry has the potential to optimize model input preparation and ultimately improve output quality.

6.3 Comprehensive Evaluation and Benchmarking

To thoroughly establish OverHAuL’s effectiveness, extensive large-scale evaluation beyond the initial 10-project corpus is imperative. Applying the tool to repositories indexed in the clib package manager [84], which encompasses hundreds of C libraries, would test scalability and robustness across diverse real-world settings. Such a broad benchmark would also enable systematic comparisons against state-of-the-art automated fuzzing frameworks like OSS-Fuzz-Gen and AutoGen, elucidating OverHAuL’s relative strengths and identifying areas for improvement [54], [56].

Complementing broad benchmarking, detailed ablation studies dissecting the contributions of individual pipeline components and algorithmic choices will yield critical insights into what drives OverHAuL’s performance. Understanding the impact of each module will guide targeted optimizations and support evidence-based design decisions.

Furthermore, an economic analysis exploring resource consumption—such as API token usage and associated monetary costs—relative to fuzzing effectiveness would be valuable for assessing the practical viability of integrating LLM-based fuzz driver generation into continuous integration processes.

6.4 Practical Deployment and Community Engagement

From a usability perspective, embedding OverHAuL within a GitHub Actions workflow represents a practical and impactful enhancement, enabling seamless integration with developers’ existing toolchains and continuous integration pipelines. This would promote wider adoption by reducing barriers to entry and fostering real-time feedback during code development cycles.

732 Additionally, establishing a mechanism to generate and submit automated pull requests (PRs) to the
733 maintainers of fuzzed libraries—highlighting detected bugs and proposing patches—would not only
734 validate OverHAuL’s findings but also contribute tangible improvements to open-source software
735 quality. This collaborative feedback loop epitomizes the symbiosis between automated testing tools
736 and the open-source community. As an initial step, developing targeted PRs for the projects where
737 bugs were discovered during OverHAuL’s development would help facilitate practical follow-up
738 and improvements.

7 Discussion

more powerful llms -> better results

open source libraries might have been in the training data results for closed source libraries could be worse this could be mitigated with llm fine-tuning

743 **8 Conclusion**

744 Recap

Bibliography

- [1] N. Perry, M. Srivastava, D. Kumar, and D. Boneh. “Do Users Write More Insecure Code with AI Assistants?” arXiv: [2211.03622](https://arxiv.org/abs/2211.03622). (Dec. 18, 2023), [Online]. Available: <http://arxiv.org/abs/2211.03622>, pre-published.
- [2] V. J. M. Manes, H. Han, C. Han, *et al.* “The Art, Science, and Engineering of Fuzzing: A Survey.” arXiv: [1812.00140 \[cs\]](https://arxiv.org/abs/1812.00140). (Apr. 7, 2019), [Online]. Available: <http://arxiv.org/abs/1812.00140>, pre-published.
- [3] A. Takanen, J. DeMott, C. Miller, and A. Kettunen, *Fuzzing for Software Security Testing and Quality Assurance* (Information Security and Privacy Library), Second edition. Boston London Norwood, MA: Artech House, 2018, 1 p., ISBN: 978-1-63081-519-6.
- [4] M. Sutton, A. Greene, and P. Amini, *Fuzzing: Brute Force Vulnerability Discovery*. Upper Saddle River, NJ: Addison-Wesley, 2007, 543 pp., ISBN: 978-0-321-44611-4.
- [5] N. Rathaus and G. Evron, *Open Source Fuzzing Tools*, G. Evron, Ed. Burlington, MA: Syngress Pub, 2007, 199 pp., ISBN: 978-1-59749-195-2.
- [6] B. P. Miller, L. Fredriksen, and B. So, “An empirical study of the reliability of UNIX utilities,” *Commun. ACM*, vol. 33, no. 12, pp. 32–44, Dec. 1, 1990, ISSN: 0001-0782. DOI: [10.1145/96267.96279](https://doi.org/10.1145/96267.96279). [Online]. Available: <https://dl.acm.org/doi/10.1145/96267.96279>.
- [7] K. Serebryany, D. Bruening, A. Potapenko, and D. Vyukov, “AddressSanitizer: A fast address sanity checker,” in *2012 USENIX Annual Technical Conference (USENIX ATC 12)*, 2012, pp. 309–318. [Online]. Available: <https://www.usenix.org/conference/atc12/technical-sessions/presentation/serebryany>.
- [8] LLVM Project. “libFuzzer – a library for coverage-guided fuzz testing. — LLVM 21.0.0git documentation.” (2025), [Online]. Available: <https://llvm.org/docs/LibFuzzer.html>.
- [9] A. Rebert, S. K. Cha, T. Avgerinos, *et al.*, “Optimizing seed selection for fuzzing,” in *Proceedings of the 23rd USENIX Conference on Security Symposium*, ser. SEC’14, USA: USENIX Association, Aug. 20, 2014, pp. 861–875, ISBN: 978-1-931971-15-7.
- [10] OWASP Foundation. “Fuzzing.” (), [Online]. Available: <https://owasp.org/www-community/Fuzzing>.
- [11] Blackduck, Inc. “Heartbleed Bug.” (Mar. 7, 2025), [Online]. Available: <https://heartbleed.com/>.
- [12] CVE Program. “CVE - CVE-2014-0160.” (2014), [Online]. Available: <https://cve.mitre.org/cgi-bin/cvename.cgi?name=cve-2014-0160>.
- [13] The OpenSSL Project, *Openssl/openssl*, OpenSSL, Jul. 15, 2025. [Online]. Available: <https://github.com/openssl/openssl>.
- [14] D. Wheeler. “How to Prevent the next Heartbleed.” (2014), [Online]. Available: <https://dwheeler.com/essays/heartbleed.html>.
- [15] GNU Project. “Bash - GNU Project - Free Software Foundation.” (), [Online]. Available: <https://www.gnu.org/software/bash/>.
- [16] M. Zalewski. “American fuzzy lop.” (), [Online]. Available: <https://lcamtuf.coredump.cx/afl/>.
- [17] J. Saarinen. “Further flaws render Shellshock patch ineffective,” iTnews. (Sep. 29, 2014), [Online]. Available: <https://www.itnews.com.au/news/further-flaws-render-shellshock-patch-ineffective-396256>.

- [18] T. Simonite, “This Bot Hunts Software Bugs for the Pentagon,” *Wired*, Jun. 1, 2020, ISSN: 1059-1028. [Online]. Available: <https://www.wired.com/story/bot-hunts-software-bugs-pentagon/>.
- [19] M. Heuse, H. Eißfeldt, A. Fioraldi, and D. Maier, *AFL++*, version 4.00c, Jan. 2022. [Online]. Available: <https://github.com/AFLplusplus/AFLplusplus>.
- [20] LLVM Project. “The LLVM Compiler Infrastructure Project.” (2025), [Online]. Available: <https://llvm.org/>.
- [21] F. Bellard, P. Maydell, and QEMU Team, *QEMU*, version 10.0.2, May 29, 2025. [Online]. Available: <https://www.qemu.org/>.
- [22] Unicorn Engine, *Unicorn-engine/unicorn*, Unicorn Engine, Jul. 15, 2025. [Online]. Available: <https://github.com/unicorn-engine/unicorn>.
- [23] H. Li, “Language models: Past, present, and future,” *Commun. ACM*, vol. 65, no. 7, pp. 56–63, Jun. 21, 2022, ISSN: 0001-0782. DOI: 10.1145/3490443. [Online]. Available: <https://dl.acm.org/doi/10.1145/3490443>.
- [24] Z. Wang, Z. Chu, T. V. Doan, S. Ni, M. Yang, and W. Zhang, “History, development, and principles of large language models: An introductory survey,” *AI and Ethics*, vol. 5, no. 3, pp. 1955–1971, Jun. 1, 2025, ISSN: 2730-5961. DOI: 10.1007/s43681-024-00583-7. [Online]. Available: <https://doi.org/10.1007/s43681-024-00583-7>.
- [25] D. Bahdanau, K. Cho, and Y. Bengio. “Neural Machine Translation by Jointly Learning to Align and Translate.” arXiv: 1409.0473 [cs, stat]. (May 19, 2016), [Online]. Available: <http://arxiv.org/abs/1409.0473>, pre-published.
- [26] A. Vaswani, N. Shazeer, N. Parmar, *et al.* “Attention Is All You Need.” arXiv: 1706.03762 [cs]. (Aug. 1, 2023), [Online]. Available: <http://arxiv.org/abs/1706.03762>, pre-published.
- [27] J. Devlin, M.-W. Chang, K. Lee, and K. Toutanova. “BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding.” arXiv: 1810.04805 [cs]. (May 24, 2019), [Online]. Available: <http://arxiv.org/abs/1810.04805>, pre-published.
- [28] A. Radford, K. Narasimhan, T. Salimans, and I. Sutskever, “Improving language understanding by generative pre-training,” 2018. [Online]. Available: <https://www.mikecaptain.com/resources/pdf/GPT-1.pdf>.
- [29] A. Radford, J. Wu, R. Child, D. Luan, D. Amodei, and I. Sutskever, “Language models are unsupervised multitask learners,” *OpenAI blog*, vol. 1, no. 8, p. 9, 2019. [Online]. Available: <https://storage.prod.researchhub.com/uploads/papers/2020/06/01/language-models.pdf>.
- [30] T. B. Brown, B. Mann, N. Ryder, *et al.* “Language Models are Few-Shot Learners.” arXiv: 2005.14165 [cs]. (Jul. 22, 2020), [Online]. Available: <http://arxiv.org/abs/2005.14165>, pre-published.
- [31] OpenAI, J. Achiam, S. Adler, *et al.* “GPT-4 Technical Report.” arXiv: 2303.08774 [cs]. (Mar. 4, 2024), [Online]. Available: <http://arxiv.org/abs/2303.08774>, pre-published.
- [32] Anthropic. “Claude.” (2025), [Online]. Available: <https://claude.ai/new>.
- [33] DeepSeek-AI, D. Guo, D. Yang, *et al.* “DeepSeek-R1: Incentivizing Reasoning Capability in LLMs via Reinforcement Learning.” arXiv: 2501.12948 [cs]. (Jan. 22, 2025), [Online]. Available: <http://arxiv.org/abs/2501.12948>, pre-published.
- [34] A. Grattafiori, A. Dubey, A. Jauhri, *et al.* “The Llama 3 Herd of Models.” arXiv: 2407.21783 [cs]. (Nov. 23, 2024), [Online]. Available: <http://arxiv.org/abs/2407.21783>, pre-published.
- [35] OpenAI. “ChatGPT.” (2025), [Online]. Available: <https://chatgpt.com>.
- [36] Google. “Google Gemini,” Gemini. (2025), [Online]. Available: <https://gemini.google.com>.
- [37] J. Wei, X. Wang, D. Schuurmans, *et al.* “Chain-of-Thought Prompting Elicits Reasoning in Large Language Models.” arXiv: 2201.11903 [cs]. (Jan. 10, 2023), [Online]. Available: <http://arxiv.org/abs/2201.11903>, pre-published.

- [38] S. Yao, D. Yu, J. Zhao, *et al.* “Tree of Thoughts: Deliberate Problem Solving with Large Language Models.” arXiv: [2305.10601](https://arxiv.org/abs/2305.10601) [cs]. (Dec. 3, 2023), [Online]. Available: [http://arxiv.org/abs/2305.10601](https://arxiv.org/abs/2305.10601), pre-published.
- [39] P. Lewis, E. Perez, A. Piktus, *et al.* “Retrieval-Augmented Generation for Knowledge-Intensive NLP Tasks.” arXiv: [2005.11401](https://arxiv.org/abs/2005.11401) [cs]. (Apr. 12, 2021), [Online]. Available: [http://arxiv.org/abs/2005.11401](https://arxiv.org/abs/2005.11401), pre-published.
- [40] S. Yao, J. Zhao, D. Yu, *et al.* “ReAct: Synergizing Reasoning and Acting in Language Models.” arXiv: [2210.03629](https://arxiv.org/abs/2210.03629). (Mar. 10, 2023), [Online]. Available: [http://arxiv.org/abs/2210.03629](https://arxiv.org/abs/2210.03629), pre-published.
- [41] AnySphere. “Cursor - The AI Code Editor.” (2025), [Online]. Available: <https://cursor.com/>.
- [42] Microsoft. “GitHub Copilot · Your AI pair programmer,” GitHub. (2025), [Online]. Available: <https://github.com/features/copilot>.
- [43] E. Nijkamp, B. Pang, H. Hayashi, *et al.*, “CodeGen: An open large language model for code with multi-turn program synthesis,” *ICLR*, 2023.
- [44] E. Nijkamp, H. Hayashi, C. Xiong, S. Savarese, and Y. Zhou, “CodeGen2: Lessons for training llms on programming and natural languages,” *ICLR*, 2023.
- [45] OpenAI. “Introducing GPT-4.1 in the API.” (Apr. 14, 2025), [Online]. Available: <https://openai.com/index/gpt-4-1/>.
- [46] A. Sarkar and I. Drosos. “Vibe coding: Programming through conversation with artificial intelligence.” arXiv: [2506.23253](https://arxiv.org/abs/2506.23253) [cs]. (Jun. 29, 2025), [Online]. Available: [http://arxiv.org/abs/2506.23253](https://arxiv.org/abs/2506.23253), pre-published.
- [47] D. Ganguly, S. Iyengar, V. Chaudhary, and S. Kalyanaraman. “Proof of Thought : Neurosymbolic Program Synthesis allows Robust and Interpretable Reasoning.” arXiv: [2409.17270](https://arxiv.org/abs/2409.17270). (Sep. 25, 2024), [Online]. Available: [http://arxiv.org/abs/2409.17270](https://arxiv.org/abs/2409.17270), pre-published.
- [48] A. d’Avila Garcez and L. C. Lamb. “Neurosymbolic AI: The 3rd Wave.” arXiv: [2012.05876](https://arxiv.org/abs/2012.05876). (Dec. 16, 2020), [Online]. Available: [http://arxiv.org/abs/2012.05876](https://arxiv.org/abs/2012.05876), pre-published.
- [49] M. Gaur and A. Sheth. “Building Trustworthy NeuroSymbolic AI Systems: Consistency, Reliability, Explainability, and Safety.” arXiv: [2312.06798](https://arxiv.org/abs/2312.06798). (Dec. 5, 2023), [Online]. Available: [http://arxiv.org/abs/2312.06798](https://arxiv.org/abs/2312.06798), pre-published.
- [50] G. Grov, J. Halvorsen, M. W. Eckhoff, B. J. Hansen, M. Eian, and V. Mavroeidis. “On the use of neurosymbolic AI for defending against cyber attacks.” arXiv: [2408.04996](https://arxiv.org/abs/2408.04996). (Aug. 9, 2024), [Online]. Available: [http://arxiv.org/abs/2408.04996](https://arxiv.org/abs/2408.04996), pre-published.
- [51] A. Sheth, K. Roy, and M. Gaur. “Neurosymbolic AI – Why, What, and How.” arXiv: [2305.00813](https://arxiv.org/abs/2305.00813) [cs]. (May 1, 2023), [Online]. Available: [http://arxiv.org/abs/2305.00813](https://arxiv.org/abs/2305.00813), pre-published.
- [52] D. Tilwani, R. Venkataramanan, and A. P. Sheth. “Neurosymbolic AI approach to Attribution in Large Language Models.” arXiv: [2410.03726](https://arxiv.org/abs/2410.03726). (Sep. 30, 2024), [Online]. Available: [http://arxiv.org/abs/2410.03726](https://arxiv.org/abs/2410.03726), pre-published.
- [53] Z. Li, S. Dutta, and M. Naik. “IRIS: LLM-Assisted Static Analysis for Detecting Security Vulnerabilities.” arXiv: [2405.17238](https://arxiv.org/abs/2405.17238) [cs]. (Apr. 6, 2025), [Online]. Available: [http://arxiv.org/abs/2405.17238](https://arxiv.org/abs/2405.17238), pre-published.
- [54] Y. Sun, “Automated Generation and Compilation of Fuzz Driver Based on Large Language Models,” in *Proceedings of the 2024 9th International Conference on Cyber Security and Information Engineering*, ser. ICCSIE ’24, New York, NY, USA: Association for Computing Machinery, Dec. 3, 2024, pp. 461–468, ISBN: 979-8-4007-1813-7. DOI: [10.1145/3689236.3689272](https://doi.org/10.1145/3689236.3689272). [Online]. Available: <https://doi.org/10.1145/3689236.3689272>.

- [55] D. Wang, G. Zhou, L. Chen, D. Li, and Y. Miao. “ProphetFuzz: Fully Automated Prediction and Fuzzing of High-Risk Option Combinations with Only Documentation via Large Language Model.” arXiv: 2409.00922 [cs]. (Sep. 1, 2024), [Online]. Available: <http://arxiv.org/abs/2409.00922>, pre-published.
- [56] D. Liu, O. Chang, J. metzman, M. Sablotny, and M. Maruseac, *OSS-fuzz-gen: Automated fuzz target generation*, version <https://github.com/google/oss-fuzz-gen/tree/v1.0>, May 2024. [Online]. Available: <https://github.com/google/oss-fuzz-gen>.
- [57] H. Green and T. Avgerinos, “GraphFuzz: Library API fuzzing with lifetime-aware dataflow graphs,” in *Proceedings of the 44th International Conference on Software Engineering*, Pittsburgh Pennsylvania: ACM, May 21, 2022, pp. 1070–1081. DOI: 10.1145/3510003.3510228. [Online]. Available: <https://dl.acm.org/doi/10.1145/3510003.3510228>.
- [58] B. Jeong, J. Jang, H. Yi, *et al.*, “UTopia: Automatic Generation of Fuzz Driver using Unit Tests,” in *2023 IEEE Symposium on Security and Privacy (SP)*, May 2023, pp. 2676–2692. DOI: 10.1109/SP46215.2023.10179394. [Online]. Available: <https://ieeexplore.ieee.org/abstract/document/10179394>.
- [59] Y. Deng, C. S. Xia, C. Yang, S. D. Zhang, S. Yang, and L. Zhang. “Large Language Models are Edge-Case Fuzzers: Testing Deep Learning Libraries via FuzzGPT.” arXiv: 2304.02014 [cs]. (Apr. 4, 2023), [Online]. Available: <http://arxiv.org/abs/2304.02014>, pre-published.
- [60] Y. Deng, C. S. Xia, H. Peng, C. Yang, and L. Zhang, “Large Language Models Are Zero-Shot Fuzzers: Fuzzing Deep-Learning Libraries via Large Language Models,” in *Proceedings of the 32nd ACM SIGSOFT International Symposium on Software Testing and Analysis*, ser. ISSTA 2023, New York, NY, USA: Association for Computing Machinery, Jul. 13, 2023, pp. 423–435, ISBN: 979-8-4007-0221-1. DOI: 10.1145/3597926.3598067. [Online]. Available: <https://dl.acm.org/doi/10.1145/3597926.3598067>.
- [61] K. Ispoglou, D. Austin, V. Mohan, and M. Payer, “FuzzGen: Automatic fuzzer generation,” in *29th USENIX Security Symposium (USENIX Security 20)*, 2020, pp. 2271–2287. [Online]. Available: <https://www.usenix.org/conference/usenixsecurity20/presentation/ispoglou>.
- [62] D. Babić, S. Bucur, Y. Chen, *et al.*, “FUDGE: Fuzz driver generation at scale,” in *Proceedings of the 2019 27th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering*, Tallinn Estonia: ACM, Aug. 12, 2019, pp. 975–985, ISBN: 978-1-4503-5572-8. DOI: 10.1145/3338906.3340456. [Online]. Available: <https://dl.acm.org/doi/10.1145/3338906.3340456>.
- [63] C. Cadar, D. Dunbar, and D. Engler, “KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs,” presented at the USENIX Symposium on Operating Systems Design and Implementation, Dec. 8, 2008. [Online]. Available: <https://www.semanticscholar.org/paper/KLEE%3A-Unassisted-and-Automatic-Generation-of-Tests-Cadar-Dunbar/0b93657965e506dfbd56fbc1c1d4b9666b1d01c8>.
- [64] A. Arya, O. Chang, J. Metzman, K. Serebryany, and D. Liu, *OSS-Fuzz*, Apr. 8, 2025. [Online]. Available: <https://github.com/google/oss-fuzz>.
- [65] N. Sasirekha, A. Edwin Robert, and M. Hemalatha, “Program Slicing Techniques and its Applications,” *International Journal of Software Engineering & Applications*, vol. 2, no. 3, pp. 50–64, Jul. 31, 2011, ISSN: 09762221. DOI: 10.5121/ijsea.2011.2304. [Online]. Available: <http://www.airccse.org/journal/ijsea/papers/0711ijsea04.pdf>.
- [66] OSS-Fuzz. “OSS-Fuzz Documentation,” OSS-Fuzz. (2025), [Online]. Available: <https://google.github.io/oss-fuzz/>.
- [67] Google, *Google/clusterfuzz*, Google, Apr. 9, 2025. [Online]. Available: <https://github.com/google/clusterfuzz>.
- [68] Google, *Google/fuzztest*, Google, Jul. 10, 2025. [Online]. Available: <https://github.com/google/fuzztest>.
- [69] Google, *Google/honggfuzz*, Google, Jul. 10, 2025. [Online]. Available: <https://github.com/google/honggfuzz>.

- [70] D. Liu, J. Metzman, O. Chang, and G. O. S. S. Team. “AI-Powered Fuzzing: Breaking the Bug Hunting Barrier,” Google Online Security Blog. (Aug. 16, 2023), [Online]. Available: <https://security.googleblog.com/2023/08/ai-powered-fuzzing-breaking-bug-hunting.html>.
- [71] Open Source Security Foundation (OpenSSF), *OSSF/fuzz-introspector*, Open Source Security Foundation (OpenSSF), Jun. 30, 2025. [Online]. Available: <https://github.com/ossf/fuzz-introspector>.
- [72] L. Thomason, *Leethomason/tinyxml2*, Jul. 10, 2025. [Online]. Available: <https://github.com/leethomason/tinyxml2>.
- [73] OSS-Fuzz Maintainers. “Introducing LLM-based harness synthesis for unfuzzed projects,” OSS-Fuzz blog. (May 27, 2024), [Online]. Available: <https://blog.oss-fuzz.com/posts/introducing-llm-based-harness-synthesis-for-unfuzzed-projects/>.
- [74] O. Khattab, A. Singhvi, P. Maheshwari, *et al.* “DSPy: Compiling Declarative Language Model Calls into Self-Improving Pipelines.” arXiv: 2310.03714 [cs]. (Oct. 5, 2023), [Online]. Available: <http://arxiv.org/abs/2310.03714>, pre-published.
- [75] Y. Lyu, Y. Xie, P. Chen, and H. Chen. “Prompt Fuzzing for Fuzz Driver Generation.” arXiv: 2312.17677 [cs]. (May 29, 2024), [Online]. Available: <http://arxiv.org/abs/2312.17677>, pre-published.
- [76] H. Chase, *LangChain*, Oct. 2022. [Online]. Available: <https://github.com/langchain-ai/langchain>.
- [77] Langchain Project, *Langchain-ai/langgraph*, LangChain, May 21, 2025. [Online]. Available: <https://github.com/langchain-ai/langgraph>.
- [78] J. Liu, *LlamaIndex*, Nov. 2022. DOI: 10.5281/zenodo.1234. [Online]. Available: https://github.com/jerryliu/llama_index.
- [79] A. Cedilnik, B. Hoffman, B. King, K. Martin, and A. Neundorf, *CMake - Upgrade Your Software Build System*, 2000. [Online]. Available: <https://cmake.org/>.
- [80] S. I. Feldman, “Make — a program for maintaining computer programs,” *Software: Practice and Experience*, vol. 9, no. 4, pp. 255–265, 1979, ISSN: 1097-024X. DOI: 10.1002/spe.4380090402. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/spe.4380090402>.
- [81] E. Martin, *Ninja-build/ninja*, ninja-build, Jul. 14, 2025. [Online]. Available: <https://github.com/ninja-build/ninja>.
- [82] J. Pakkanen, *Mesonbuild/meson*, The Meson Build System, Jul. 14, 2025. [Online]. Available: <https://github.com/mesonbuild/meson>.
- [83] Google, *Google/atheris*, Google, Apr. 9, 2025. [Online]. Available: <https://github.com/google/atheris>.
- [84] Clibs Project. “Clib Packages,” GitHub. (2025), [Online]. Available: <https://github.com/clibs/clib/wiki/Packages>.