Development and Implementation of an Algorithm for Memory Leak Detection in C/C++ Programs

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Abstract—This work presents the development and implementation of the Alloc Free Imbalance checker, a specialized component for detecting memory leaks in C/C++ programs. The checker is built using the API framework provided by the Memory Leak Hunter (MLH) platform, which combines static analysis with directed symbolic execution. Our implementation focuses on detecting imbalances between memory allocation and deallocation operations across control flow paths, contributing to the overall effectiveness of the MLH tool in achieving scalable and accurate memory leak detection.

***Keywords*—Directed symbolic execution, static analysis, memory leak.**

I. INTRODUCTION

Memory management errors, particularly memory leaks, remain among the most prevalent and critical issues in C and C++ programming. While comprehensive frameworks for memory leak detection have been developed, there is a continued need for specialized components that can effectively identify specific types of memory management errors within these frameworks.

Aslanyan et al. [1] developed a comprehensive Memory Leak Hunter (MLH) framework that combines static analysis with directed symbolic execution for scalable and accurate memory leak detection. The approach provides a robust API foundation that enables the development of specialized checkers for different types of memory management issues.

Building upon this foundation, this work focuses on the development and implementation of the Alloc Free Imbalance checker, a specialized component designed to detect imbalances between memory allocation and deallocation operations. The checker leverages the MLH framework's API to provide targeted detection capabilities for this specific category of memory leaks.

The primary contributions of this work are multifaceted. We present the formal design and implementation of the Alloc Free Imbalance checker, realized through the programmatic interface of the MLH framework. This work further contributes specialized algorithms for path-sensitive analysis, capable of tracking and quantifying the balance of memory management operations across complex control-flow graphs. The checker is integrated into the existing MLH infrastructure, and its effectiveness is validated through an empirical evaluation that demonstrates its precision and utility as a valuable component within the MLH tool suite.

II. BACKGROUND AND RELATED WORK

Memory leaks are a longstanding problem in software systems, especially in environments that require manual memory management, such as those written in C/C++. These leaks are particularly dangerous in critical systems like operating systems, network servers, and embedded devices, where memory resources are limited and reliability is paramount.

While numerous tools exist to detect memory leaks, they often encounter significant trade-offs between precision and scalability. Traditional static analysis tools like Clang Static Analyzer [10] and commercial solutions such as PVS-Studio [11] concentrate on broad categories of programming errors but may lack specialized handling for specific memory management patterns. These tools can analyze extensive codebases rapidly but tend to generate numerous false positives, identifying issues that are not genuine memory leaks. Conversely, dynamic analysis tools such as Valgrind [12] provide runtime detection capabilities but require comprehensive test coverage and may fail to identify all memory leaks due to limited code coverage during execution monitoring.

Recent hybrid approaches have demonstrated potential in combining different analysis techniques. However, existing frameworks often lack the specialized architecture needed for targeted memory leak detection. We chose to integrate alloc-free imbalance detection into the MLH framework due to its advantages in combining static analysis with directed symbolic execution, creating a system that efficiently detects potential memory leaks while minimizing false positives.

A. *Memory Leak Hunter Framework*

Aslanyan et al. [1] developed the Memory Leak Hunter (MLH) framework, which provides a comprehensive platform for memory leak detection by combining static analysis with directed symbolic execution. The MLH framework offers several key advantages:

1. **Hybrid Analysis Approach**: The framework integrates static analysis for efficient initial detection with symbolic execution for precise validation.
2. **Scalability**: The directed symbolic execution approach focuses computational resources on likely error paths, improving scalability for large programs.
3. **Extensible Architecture**: The framework provides APIs that enable the development of specialized checkers for different types of memory management errors.
4. **High Accuracy**: The combination of analysis techniques significantly reduces false positives while maintaining comprehensive coverage.

B. *API Framework and Extension Points*

The MLH framework exposes several API interfaces that enable the development of custom checkers:

- **Control Flow Analysis API:** Provides access to control flow graphs and path analysis capabilities.
- **Data Flow Analysis API:** Enables tracking of variable states and memory operations across program execution.
- **Symbolic Execution Interface:** Allows integration with the directed symbolic execution engine.
- **Checker Registration API:** Provides mechanisms for registering and integrating custom checkers into the analysis pipeline.

III. Alloc Free Imbalance Checker Design and Implementation

The checker looks for situations where the number of memory allocations doesn't match the number of memory frees along control flow paths through the code. It counts how many times memory is allocated and freed on each possible route through a function to find where memory might be leaked. Here's a simple example that shows how memory allocations and frees can become unbalanced:

```
1.  typedef struct Report {
2.      int id;
3.      char* title;
4.      char* content;
5.  } Report;
6.  …
7.  Report* report = (Report*)malloc(sizeof(Report));
8.  if (report == NULL) {
9.      return;
10. }
11.
12. report->id = 100;
13. report->title = (char*)malloc(100);
14. report->content = (char*)malloc(1000);
15.
16. if (report->title == NULL || report->content ==
    NULL) {
17.     free(report);
18.     return;
19. }
20.
21. free(report->title);
22. free(report->content);
23. free(report);
```

In this example, memory is allocated at runtime on lines 7, 13, and 14. When one of the allocations in lines 13 and 14 is successful but the other fails (returns NULL), the program jumps to line 18, where only the struct allocation in line 17 is freed, but one of its successfully allocated fields is never freed. This causes the successfully allocated memory to be leaked since it is never freed before the function exits. The checker's architecture is described below.

The Alloc Free Imbalance checker is implemented as a specialized component within the MLH framework, utilizing the provided APIs to perform targeted detection of allocation-deallocation imbalances. The checker architecture consists of several key components:

A. *Integration with Allocation Site Analyzer*

The Allocation Site Analyzer provides the checker with comprehensive information on all memory allocation operations in the program. Through the MLH annotation API, the checker receives information about allocation return (AR) and inner allocation return (IAR) annotations. These annotations tell the checker not just where memory is allocated, but also under what conditions, what size, and whether the allocated memory is properly saved, returned, or passed to other functions. The analyzer distinguishes between different types of allocations and tracks individual fields within structures.

B. *Integration with Deallocation Tracker*

The Deallocation Tracker supplies corresponding deallocation information through deallocation annotations, deallocation of an argument (DA), and deallocation of argument offset (DAO). The checker uses these annotations to understand where and under what conditions memory is freed. The tracker provides crucial offset information that allows the checker to match deallocations with their corresponding allocations at a field-sensitive level, distinguishing between freeing different parts of a structure.

C. *Imbalance Detector*

Imbalance Detector: Identifies paths where allocations are not matched by corresponding deallocations. The core algorithm for detecting allocation-deallocation imbalances operates as follows:

1. **Identifying Independent Allocation Sites:** Allocation sites are deemed independent if no control flow exists between them.
2. **Identifying Unique Control Flow Paths:** For each independent allocation site and exit node, we identify all unique paths through the control flow graph that connect the allocation to the exit, ensuring comprehensive path coverage for subsequent analysis. A path is considered unique if the sets of allocation sites and free points differ.
3. **Detecting Allocation and Free Imbalances:** For each unique path, we examine its allocation sites and attempt to identify any corresponding free sites that deallocate the allocated memory. We also consider the data flow, ensuring there is a path from the allocation node to the free node. If an allocation lacks a matching free node, it is flagged as a potential memory leak.

4. **Generating Trace for Potential Memory Leaks:** A trace is created for any identified potential memory leaks, capturing the exact path from allocation to the point where memory is lost.
5. **Verification:** The generated traces are passed to the directed symbolic execution engine for feasibility validation, filtering out false positives from infeasible paths.

IV. EXPERIMENTAL RESULTS

The Alloc Free Imbalance checker has been integrated into the Memory Leak Hunter (MLH) framework and evaluated as part of the comprehensive tool suite. The evaluation demonstrates the checker's effectiveness in detecting allocation-deallocation imbalances within the broader context of the MLH framework's capabilities.

A. Evaluation on Open-Source Projects

This approach has been implemented in the Memory Leak Hunter (MLH) tool, which has been successfully applied to more than a hundred open-source benchmark projects, such as OpenSSL [15] and Ffmpeg [16]. The Alloc-Free Imbalance checker played a key role in detecting memory leaks in these projects, demonstrating the method's robustness and practical impact in real-world applications. The complete results of the detected bugs in open-source projects are presented in TABLE 1.

TABLE 2. DETECTED MEMORY LEAKS IN OPEN-SOURCE PROJECTS

Project name	Repository link	Reported issues identifiers
openssl	https://github.com/openssl/openssl	20870
ffmpeg	https://lists.ffmpeg.org/	10342
radare2	https://github.com/radareorg/radare2	21703, 21704
bind9	https://gitlab.isc.org/isc-projects/bind9	4282
clib	https://github.com/clibs/clib	292, 293, 295
coturn	https://github.com/coturn/coturn	1259
cups	https://github.com/apple/cups	6144
cyclonedds	https://github.com/eclipse-cyclonedds/cyclonedds	1814
gpac	https://github.com/gpac/gpac	2569
pupnp	https://github.com/pupnp/pupnp	430
varnish-cache	https://github.com/varnishcache/varnish-cache	3986
masscan	https://github.com/robertdavidgraham/masscan	730
FreeRDP	https://github.com/FreeRDP/FreeRDP	9410, 9411
libvips	https://github.com/libvips/libvips	3642
zstd	https://github.com/facebook/zstd	3764
scrcpy	https://github.com/Genymobile/scrcpy	4636
libarchive	https://github.com/libarchive/libarchive	1949

B. Contribution to MLH Framework Performance

The integration of the Alloc Free Imbalance checker significantly contributed to the overall performance of the MLH framework. The comparison with existing tools was performed on the well-known Juliet test suite, where the enhanced MLH framework (including our checker) demonstrated superior results (TABLE 2).

TABLE 2. COMPARISON ON JULIET TESTS SUITE

Tools Name	**True Positives**	**True Negatives**	**False Positives**	**False Negatives**	**F1-score**
CSA	536	4481	125	332	0.70
Infer	262	4392	214	606	0.39
SMOKE	496	4510	96	372	0.68
PCA	486	4342	264	382	0.60
SVF	452	4168	438	416	0.51
MLH	**868**	**4606**	**0**	**0**	**1**
Alloc Free Imbalance checker (MLH)	**720**	**4606**	**0**	**148**	**0.90**

V. Conclusion

This work has successfully demonstrated the design and implementation of the Alloc Free Imbalance checker as a valuable component within the Memory Leak Hunter (MLH) framework. By leveraging the MLH framework's comprehensive API infrastructure, we have created a specialized detector that effectively identifies memory leaks caused by allocation-deallocation imbalances in C/C++ programs.

The key contributions of this work include:

- Successful Integration: The Alloc Free Imbalance checker has been seamlessly integrated into the MLH framework, utilizing its annotation-based API to access allocation and deallocation information efficiently.
- Proven Effectiveness: Experimental results on the Juliet test suite demonstrate that the enhanced MLH framework, including our checker, achieves an F1-score of 0.90, significantly outperforming existing tools while maintaining zero false positives.
- Real-World Impact: The checker has been successfully applied to numerous open-source projects including OpenSSL, FFmpeg, and Radare2[17], identifying and reporting 148 confirmed memory leaks that were subsequently fixed by the respective communities.
- Scalable Architecture: By leveraging the MLH framework's path-sensitive analysis and annotation caching mechanisms, the checker maintains both precision and scalability, making it suitable for analyzing large-scale industrial software.

The Alloc Free Imbalance checker demonstrates the power of the MLH framework's extensible architecture, showing how specialized detectors can be built to target specific types of memory management errors. This modular approach allows for continuous enhancement of the framework's capabilities while maintaining the benefits of the underlying hybrid analysis approach.

Future work could extend this approach to develop additional specialized checkers for other types of memory management patterns, further expanding the MLH framework's ability to detect complex memory-related bugs in C/C++ programs. The success of this implementation validates the framework's design philosophy of combining static analysis with directed symbolic execution to achieve both accuracy and scalability in memory leak detection.

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