

# RCANARY: Detecting Memory Leaks Across Semi-automated Memory Management Boundary in Rust

Mohan Cui  
School of Computer Science,  
Fudan University

Hui Xu\*  
School of Computer Science,  
Fudan University

Suran Sun  
School of Computer Science,  
Fudan University

Yangfan Zhou  
School of Computer Science,  
Fudan University

## ABSTRACT

Rust is an effective system programming language that guarantees memory safety via compile-time verifications. It employs a novel ownership-based resource management model to facilitate automated resource deallocation. It is anticipated that this model will eliminate memory leaks. However, we observed that user intervention driving semi-automated management is prone to introducing leaks. In contrast to violating memory-safety guarantees via the *unsafe* keyword, the leak breached boundary is implicit with no compiler alerting.

In this paper, we present RCANARY, a static, non-intrusive, and fully automated model checker to detect leaks across the semi-automated boundary. It adopts a precise encoder to abstract data with heap allocation and formalizes a refined leak-free memory model based on boolean satisfiability. RCANARY is implemented as an external component of Cargo and can generate constraints via MIR data flow. We evaluate it using flawed package benchmarks collected from the pull requests of prominent Rust packages. The results indicate it is possible to recall all these defects with acceptable false positives. We also apply our tool to more than 1,200 real-world crates from crates.io and GitHub, identifying 19 crates with potentially vulnerable leaks in 8.4 seconds per package.

## CCS CONCEPTS

• **Software and its engineering** → **Software defect analysis; Automated static analysis.**

## KEYWORDS

Memory Leak, Model Check, Semi-automated Memory Management, Boolean Satisfiability, Ownership, Rust

### ACM Reference Format:

Mohan Cui, Suran Sun, Hui Xu, and Yangfan Zhou. 2023. RCANARY: Detecting Memory Leaks Across Semi-automated Memory Management Boundary in Rust. In *Proceedings of arxiv pre-print versions (arxiv)*. ACM, New York, NY, USA, 12 pages. <https://doi.org/10.1145/nnnnnnn.nnnnnnn>

## 1 INTRODUCTION

Rust is an emerging, strongly-typed programming language focusing on efficiency and memory safety [45]. Ownership is a prominent design of the zero-cost abstraction in Rust [29] that can ensure memory safety without sacrificing performance. It introduces the non-lexical lifetime (NLL) to deduce the minimum lifespan of each value

in greater detail<sup>1</sup>. Using NLL, Rust can automatically deallocate resources by inserting the `drop()` instruction at the appropriate program point [32]. Additionally, Rust enables users to evade automated deallocation and manage resources in the lower control, a technique known as **semi-automated memory management**, in order to increase flexibility. Many companies and open-source projects thus switch to Rust, such as the web browser engine Servo for Firefox [1], the operating system Redox OS [42, 44, 54], the LibOS Occlum [34, 60], and the embedded system Tock OS [37–39]. In 2023, Rust will act as the second programming language in the Linux kernel<sup>2</sup>.

We observed that the semi-automated resource management model could not eliminate memory leaks in real-world Rust programs, such as issues listed in Table 4. Studying memory leak [6, 27, 48] is crucial for the system programming language. If a program consumes a significant quantity of memory but never releases it, its memory usage will continue to rise, and remote attackers can exploit this memory leak to launch a denial-of-service [14] (DoS) attack. Despite numerous studies on leak detection for C/C++ programs [9, 30, 35], to the best of our knowledge, no work has been conducted for Rust<sup>3</sup>. In a recent empirical study on Rust security [3], the researchers summarized a fine-grained categorization for safety requirements and conducted user surveys. Memory leaks have emerged as a subitem of this classification. The result shows that even though leaking memory is safe, experienced programmers still rank it fourth out of 19 categories in a vote for significance.

Leaking memory was not a safe operation from a temporal perspective. Until version 1.0, escaping from the ownership system was an unsafe intrinsic (`forget`) [33]. However, it was later marked safe due to not causing memory corruption. Once outside the unsafe scope, it is hard for developers to pinpoint ownership leaks. Also, the compiler does not provide detection support. According to our statistics, semi-automatic memory management is prevalent in the Rust community. As of 2023-01-30, we mined the latest crates from crates.io [22] and discovered that 5,717 repositories out of 103,516 employed this method. Compared to 21,506 crates using *unsafe* keyword [4, 19], the potential vulnerability in this model is a non-trivial problem for us to investigate.

We propose utilizing static analysis to detect leaks that cross the semi-automated boundary. Leak detection employs a taint-sink approach: The object created at the tainted site (construction) must

<sup>1</sup><https://rust-lang.github.io/rfcs/2094-nll.html>

<sup>2</sup><https://lore.kernel.org/lkml/20210414184604.23473-1-ojeda@kernel.org/>

<sup>3</sup>Except for FFICHECKER [41], but it is designed for Rust FFI with C based on LLVM.

\*Corresponding author.

reach the sink site (destruction) [71]. There are two types of existing static approaches: *iterative data-flow analysis* [52] and *sparse value-flow analysis* [70]. To our best knowledge, the current work is ineffective for Rust. The former monitors the values at each program point throughout the control flow, which is flow-sensitive. However, it lacks support for specific Rust syntax, such as ownership movement, partial drop, etc. The latter tracks the values sparsely from the define-use chains or the single static assignment (SSA) [2]. It is more efficient but flow-insensitive. The sparse representation does not check arbitrary state-machine properties for all program paths. In addition, some work is based on boolean satisfiability [26] to infer the owner for C/C++ programs, but it is inconsistent with the present Rust ownership design.

In this paper, we introduce rCANARY, a static, non-intrusive, and fully automated model checker to detect leaks across the semi-automated boundary. It consists of an encoder for transforming data over the type system and a refined leak-free model over the ownership syntax. The encoder can convert typed data into a bit vector, indicating which field contains heap allocation. The leak-free model is composed of formal rules based on boolean satisfiability. Our analyzer uses the encoder and formal rules to generate constraints through the MIR data flow in SMT-Lib2 syntax [43], forming a 0–1 integer equality list. We implemented rCANARY as an external component in Cargo and applied it to the existing flawed pull-request benchmarks collected from GitHub. The result demonstrates that it can recall all the issues that match our leak pattern and identify 19 crates with potentially vulnerable leaks in real-world Rust crates.

Our main contributions are summarized as follows:

- We studied the issue of memory leaks across the semi-automated memory management boundary in Rust and outlined two bug patterns. We developed an algorithm to identify them: an encoder to model data using heap allocation and a leak-free memory model with formal rules.
- We implemented rCANARY, a static, non-intrusive, and fully automated analyzer that can detect leaks in the Rust packages. It provides user-friendly diagnostics to pinpoint the buggy snippet. rCANARY will be open-sourced and can be modified for other research.
- We evaluate the effectiveness, usability, and efficiency of rCANARY. It can recall all bugs in the benchmark generated from GitHub and discover 19 crates with potentially vulnerable leaks in open-source Rust projects. It is also capable of executing fast scans for the Rust ecosystem.

## 2 PROBLEM STATEMENT

### 2.1 Why Leaks in Ownership Model?

Since an object has been constructed in the ownership model, the compiler will insert the `drop()` instruction at the appropriate program point to release it [45]. This instruction typically binds to object variables that implement Drop trait [65], and Rust regards the object as the **owner** (e.g., `Vec<T>` [68]). Rust also enables users not to instruct the automated deallocation that triggers semi-automated management. The escape hatch is `ManuallyDrop<T>` [64], a zero-cost wrapper that prevents the compiler from calling `T`'s destructor. Once the object encapsulates `ManuallyDrop`, it becomes an **orphan**

**object**. Like other smart pointers, `ManuallyDrop` can be dereferenced to disclose the inner `&T`, which can then be cast into the raw pointer `*T`.

`ManuallyDrop<T>` is a customizable design for toggling between automatic deallocation and manual release. However, this design is vulnerable to leaks if the programmers neglect to release them. In today's Rust ecosystem, user intervention is a significant cause of leaks. In this paper, we summarize two typical leak patterns across semi-automated boundaries: (i) **orphan object** missing `drop()` instruction in Mid-level Intermediate Representation (MIR); (ii) **proxy type** missing manual field deallocation in its `Drop` implementation. The above subjects will be discussed in Sections 2.2 and 2.3.

As for those values that escaped from the ownership model, we expected pointers and references to take responsibility for deallocation. As illustrated in Figure 1a, this paper assumes that each value has an **RAII token (rtoken)** to monitor deallocation. If an object variable possesses a `rtoken`, this holder is intuitively equal to the owner. The primary distinction is that references and pointers can carry `rtokens` but cannot be the Rust owners. To differentiate them, definition 2.1 is offered.

**DEFINITION 2.1.** *A heap item  $H_t^v$  is one resource  $H$  containing heap allocations and the fixed type  $t$ . An exclusive `rtoken`  $\sigma$  will be granted to monitor the deallocation when construction. The `rtoken` is transferable among variables, and the current holder is  $v$ .*

### 2.2 Motivating Example: Orphan Object

Creating an orphan object eliminates its `drop()` instruction in Rust MIR. Listing 1 illustrates an example of an orphan-object issue, and we will give the definition first.

**DEFINITION 2.2.** *An orphan object  $O_t$  is a heap item wrapped by the smart pointer `ManuallyDrop` with inner  $t$ .*

In Listing 1, we create a heap item  $H_{\text{Box}<\&\text{str}>}^{\text{buf}}$  with `rtoken`, and the current holder is object `buf` (line 2). Then `rtoken` is handed to the pointer `ptr`  $H_{\text{Box}<\&\text{str}>}^{\text{ptr}}$  inside the callee, where `buf` is encapsulated with `ManuallyDrop` (line 4). This function creates an orphan object  $O_{\text{Box}<\&\text{str}>}$  and returns a raw pointer by dereferencing `ManuallyDrop`. From the ownership perspective, the callee consumes the owner, restrains deallocation, and then returns the pointer to the caller.

As depicted in Figure 1a, after creating an orphan object, the heap item requires a variable to carry the `rtoken` and monitor its release, as no object (owner) is responsible for it. Figure 1b depicts the data flow of this leak issue: The orphan object is assigned to another variable. A leak will occur if the programmer forgets to release it. Therefore, the fixed snippet employs `drop_in_place` [66] to free this buffer (line 6), indicating that the variable `ptr` is the holder and consumes the `rtoken` during deallocation.

### 2.3 Motivating Example: Proxy Type

The proxy-type issue is caused by the unsound implementation of the Drop trait, a mutation of the orphan-object leak; the proxy type is defined as follows.

**DEFINITION 2.3.** *A proxy type  $P_t$  is a compound type  $t$  (ADT) containing at least one orphan object named proxy field.*

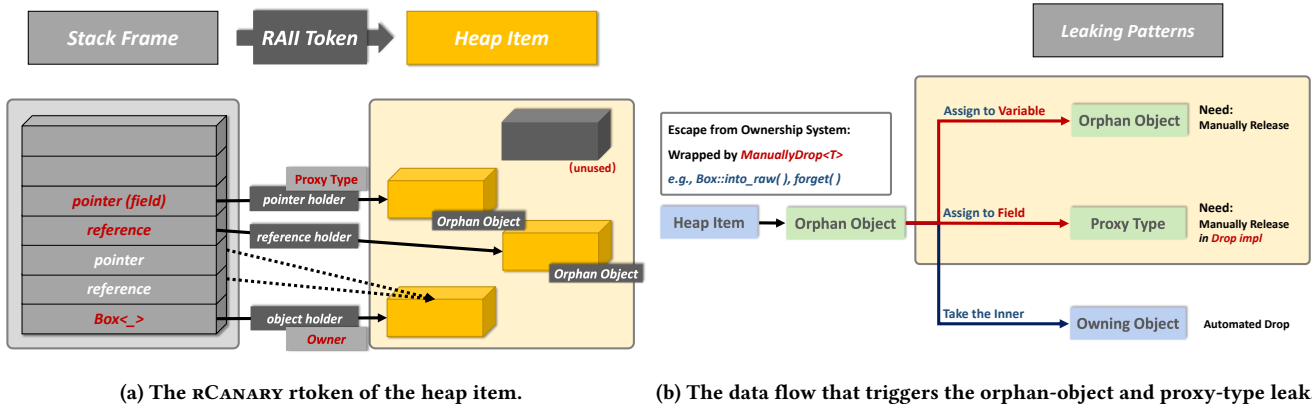


Figure 1: The relationship between RAIL Token, Owner, and Heap Item. The rtoken in Figure 1a can be held by objects, references, and pointers. In Figure 1b, each method’s first argument is wrapped in the function body with ManuallyDrop.

Listing (1) Motivating Example of Orphan-object leak.

```

1 fn main() {
2   let mut buf = Box::new("buffer");
3   // the heap item 'buf' becomes an orphan object
4   let ptr = Box::into_raw(buf);
5   // leak due to missing free operation towards 'ptr'
6   + unsafe { drop_in_place(ptr); }
7 }

```

Listing (2) Motivating Example of Proxy-type leak.

```

1 struct Proxy<T> {
2   ptr: *mut T,
3 }
4 impl<T> Drop for Proxy<T> {
5   fn drop(&mut self) {
6     // user should manually deallocate the buffer in drop
7     + unsafe { Box::from_raw(self.ptr); }
8   }
9 }
10 fn main() {
11   let mut buf = Box::new("buffer");
12   // the heap item 'buf' becomes an orphan object
13   let ptr = Box::into_raw(buf);
14   let proxy = Proxy { ptr };
15   // leak due to lacking releasing 'proxy.ptr' in drop
16 }

```

Figure 2: Motivating examples of orphan-object and proxy-type issues detected in rCANARY, caused by the lack of manual deallocation towards ManuallyDrop values.

Listing 2 demonstrates a proxy-type error linked to  $P_{\text{Buffer}<T>}$  (defined on line 4). After an orphan object  $O_{\text{Box}<\&\text{str}>}$  has been created, ptr is assigned to a proxy field (line 14). However, the default Drop implementation is ignorant that this field ought to be deallocated. Consequently, the first field will trigger a memory leak whenever a Buffer<T> object is dropped. To solve this issue, we retrieve the owner from the raw pointer to activate automated deallocation by calling `Box::from_raw` [61] (line 7).

As depicted in Figure 1b, if an orphan object is assigned to a field, although the compiler will append `drop()` to the proxy type, programmers are responsible for implementing a sound Drop method to release its proxy fields explicitly. These two patterns can encompass all leak scenarios caused by the lack of manual deallocation towards ManuallyDrop values across the semi-automated boundary, with the difference of having the `drop()` instruction in MIR.

### 3 DESIGN

In this section, we overview the design goals and present the architecture of rCANARY.

#### 3.1 Design Goal

As with most existing static analysis analyzers, rCANARY analyzes a source code representation [5, 17, 40]. We propose combining data-flow analysis and boolean satisfiability to design a static, non-intrusive, and fully automated model checker on top of the Rust MIR. We have three primary goals:

- **Abstraction.** rCANARY prioritizes heap allocation. It is expected to recognize contextual variables through their types and encode data in a proper format for subsequent model checking. In addition, the method should apply to the vast majority of Rust features, such as generic types, mono-morphization, enumerations, etc. Due to its generic type, we chose the MIR (local) variable as the foundation.
- **Usability.** rCANARY is designed as a general-purpose static analyzer for Rust programs. It will analyze each crate within a Rust package iteratively and report any potential leak errors within the semi-automated boundary. As an external component of the Rust toolchain, it should support the majority of Cargo projects and is easy to use. The workflow should be fully automated, and no user annotation is required.
- **Efficiency.** As rCANARY integrates Z3 [47] to solve constraints, the computation overhead should be considered. It should support the partitioning of levels to balance precision and efficiency, including the demand-driven (intra-procedural) taint analysis to

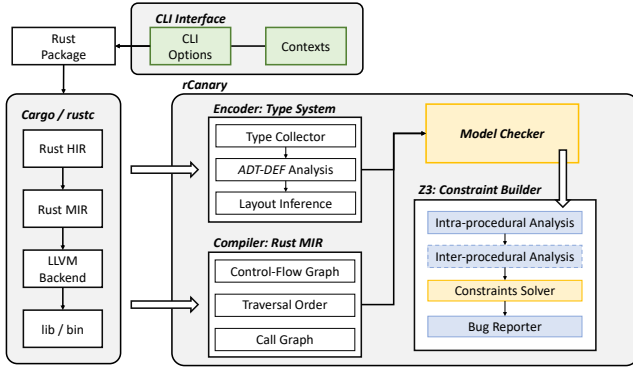


Figure 3: The workflow of rCANARY.

accomplish a rapid scan for the Rust ecosystem and an optional context-sensitive inter-procedural analysis.

### 3.2 System Architecture

The framework of rCANARY consists of three components: the CLI interface, the hybrid analyzer, and the model checker, as shown in Figure 3.

**3.2.1 CLI Interface.** The front end is a CLI program linked to the Rust toolchain. We implemented rCANARY as an external component that can be invoked as a subcommand within Cargo. We provide secondary configurations to enhance customization without impeding other compilation settings. It will be invoked after parsing the CLI parameters and initializing the configurations. The compilation metadata of the local source code will be transmitted after all MIR passes are finished. After analysis, the bug reporter will notify users of potential leaks involving buggy snippets.

**3.2.2 Hybrid Analyzer.** The first component of the back end is a hybrid analyzer developed on top of MIR. It evaluates the node order of the control-flow graph and employs the Tarjan algorithm [20] to eliminate loops. To model heap values, we designed an encoder that can transform an arbitrary type into a fixed-length bit vector. This method is efficient with linear complexity: It first analyzes the type definitions and then uses the result to accelerate type encoding with different mono-morphizations.

**3.2.3 Model Checker.** The second part of the back end is a model checker. It inputs the encoder and compilation metadata from the hybrid analyzer. We design a leak-free memory model consisting of formal rules to detect leaks across the semi-automated boundary by using Z3. The method is flow-sensitive and field-sensitive. The model checker will encode each value to generate the Z3 variable and apply the formal rule for each statement and function call to generate the Z3 assertion. Finally, the solver and bug reporter will emit the potential issue with code span for users.

## 4 ENCODER: DATA ABSTRACTION

In this section, we will introduce a precise encoder that depicts data abstraction based on Rust types. It is a general method for identifying heap items and encoding them into bit vectors.

Table 1: The classification of Rust types in Encoder.

Classification	Type	Encoding Representation			Example
		Init	Length	Data Flow	
Primitive	Boolean	[0]	1	-	true, false
	Numeric	[0]	1	-	i8, u16, isize, usize
	Textual	[0]	1	-	char, str
Object	Array	TE	1	Ctor / Ctx	[i32;1], [CString:10]
	Struct	TE	Fixed	Ctor / Ctx	Vec<T>, Box<i32>
	Enumerate	TE	Fixed	Ctor / Ctx	Option<T>
	Union	TE	Fixed	Ctor / Ctx	char, str
	Tuple	TE	Fixed	Ctor / Ctx	( ), (i32, String)
	Trait Object	[1]	1	Ctor / Ctx	dyn Clone+Display
Reference	Reference	[0]	Fixed	Ctx	&_ , &mut _
	Slice	[0]	Fixed	Ctx	&str, &[i32;1]
Pointer	Raw Pointer	[0]	Fixed	Ctx	*const _ , *mut _

<sup>1</sup> Abbreviation: TE: Type Encoding, Ctor: Constructor, Ctx: Context.

<sup>2</sup> The classification is from Rust reference but it is partially modified in this paper.

<sup>3</sup> The parameter types (generics) are defined in signatures with no constructors.

<sup>4</sup> Zero-sized types (ZSTs) are object types not listed in this table. Our encoder regards ZSTs as zeroed-length vectors ([ ]), and the operations are optimized as NOP in Z3.

### 4.1 Data Abstraction

A Rust package  $P$  contains a set of types  $T(P)$  among its variables. As shown in Table 1, any type  $t \in T(P)$  can be classified into four categories: primitive, object, reference, and pointer [23]. Each object type has a set of constructors  $C_t$  and a unique destructor  $D_t$ .  $C_t$  can be a function with a list of arguments or a local initialization.  $D_t$  is the exclusive Drop implementation for the specified type.

Every type  $t$  has an init rtoken  $R_t$  to illustrate the data abstraction in the fully initialized state.  $R_t$  is a bit vector with a fixed length for the entire lifetime. The member of  $R_t$  can take on values  $\sigma \in \{-1, 0, 1\}$ . These elements become the lifted boolean values [47], where  $\sigma = -1$  indicates uninitialized data,  $\sigma = 1$  indicates a heap item (holding heap memory), and  $\sigma = 0$  indicates the opposite (stack-allocated, freed or moved). The lifted boolean values form a semi-lattice [46]: The top element  $\top$  is  $-1$ , and the bottom element  $\perp$  is  $0$ .

**DEFINITION 4.1.** *The init rtoken of the non-enumeration type is a fixed-length bit vector. Each member denotes whether the field was initialized as a heap item.*

**DEFINITION 4.2.** *The init rtoken of the enumeration type with discriminant is a fixed bit vector of its determined variance. If not, the extent of the bit vector is zeroed (undecidable).*

In definitions 4.1 and 4.2, a field-sensitive rtoken is defined as a bit vector. It disregards the alignment and concentrates primarily on the field index. The index corresponds to the field order specified in the definition for types that are not enumerations. As with enumeration types, it requires a variance index (discriminant) since each variance may be associated with distinct types [23]. In the absence of a discriminant, the rtoken is undecidable. This rule also applies to compound types containing enumeration fields.

### 4.2 ADT-Definition Analysis

ADT-Definition [56] (AdtDef) analysis determines the possibility of a defined type becoming the heap item when fully initialized. The algorithm is in Algorithm 1.

**Algorithm 1:** ENCODER: Transform the given type into a bit vector to generate its init rtoken.

**Input:** *mir*: the mir body of each function  
**Output:** *adtdefcc*: the cache of AdtDef analysis

```

1 Function AdtDefAnalysis(mir)
2   tys ← CollectTypes(mir)
3   adtdefs ← ExtractAdtDefs(tys)
4   depG ← AnalyzeDependencies(adtdefs)
5   foreach depCC in depG do
6     depQueue ← InverseTopSort(depCC)
7     foreach adtdef in depQueue do
8       result ← HeapItemUnit(adtdef, adtdefcc)
9       result ← IsolatedParameter(adtdef, adtdefcc)
10      adtdefcc ← result
11  return adtdefcc
    
```

**Input:** *ty*: the type metadata; *adtdefcc*: the cache of AdtDef analysis

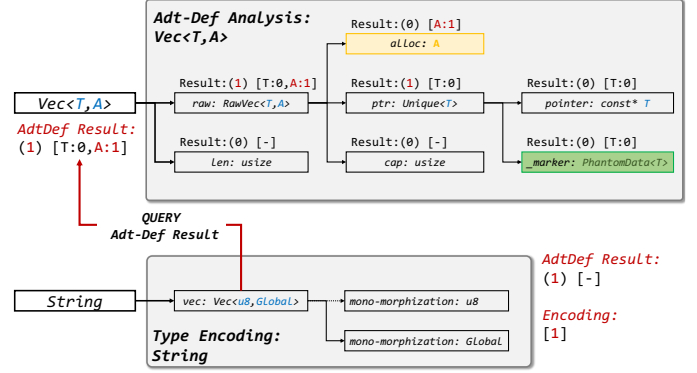
**Output:** the result of whether the input is heap item

```

12 Function EncodeField(ty, adtdefcc)
13  if HeapItemUnit(ty.adtdef, adtdefcc) then
14    return TRUE
15  foreach (generic, index) in ty.GenericArgs do
16    if IndexedIsolatedParameter(ty.adtdef, index,
17      adtdefcc) then
18      if EncodeField(generic, adtdefcc) then
19        return TRUE
19  return FALSE
    
```

**Preprocessing.** Giving an arbitrary type, it consists of type definition (AdtDef [56]) and a list of generic args (GenericArgs [57]) (e.g.,  $\text{Vec}\langle i32 \rangle$  consists of  $\text{Vec}\langle T \rangle$  and  $i32$ ). Preprocessing first invokes an inter-procedural visitor to collect all encountered types into a unique set (line 2). Those types are located not only in the local crate but also in dependencies. The code then traverses each type and extracts the definition of all compound types, also known as AdtDef (line 3). Finally, each field is flattened to generate the dependency graph for all AdtDefs (line 4). Even though Rust restricts recursion in compound types, it still permits recursion in GenericArgs (e.g.,  $\text{Vec}\langle \text{Vec}\langle i32 \rangle \rangle$ ). We break the recursion within GenericArgs and generate a directed acyclic graph (DAG).

**AdtDef and GenericArgs.** After generating the dependency graph, we will analyze if each type is already a heap item or has the potential to become one. It is crucial to summarize the form of the heap item and tackle the generic. The heap-item unit in definition 4.3 is the identity of heap items derived from the collection types in std. `PhantomData` [63] is the marker that informs the compiler that one type is a container and stores a typed  $T$  value on the heap. If this unit is contained by a flattened type, at least one field serves as a container. In definition 4.4, the isolated parameter demonstrates whether a single generic parameter can be further mono-morphized as a heap item. Regardless of whether the provided type is a heap



**Figure 4:** Example of the encoding procedure, including Adt-Def analysis for  $\text{Vec}\langle T, A \rangle$  and type encoding for  $\text{String}$ . The types within the figure have been flattened, forming a Directed Acyclic Graph (DAG). Analyze by propagating forward using reverse topological sorting.

item, if its isolated parameter mono-morphizes into an arbitrary heap-item type, this mono-morphization will produce a heap item.

**DEFINITION 4.3.** The heap-item unit has a `PhantomData<T>` field with a typed generic parameter and a pointer field to store data.

**DEFINITION 4.4.** The isolated parameter is a stand-alone and typed generic parameter (e.g.,  $T$  but not  $\&T$ ).

**Result Solving.** For each connected component in the DAG, we compute the subgraph’s inverse topological order (line 6). In this order, we will iteratively determine whether each AdtDef contains the heap-item unit and the isolated parameter recursively (lines 8, 9). The task can be simplified using inverse topo-order to determine whether each field is a heap-type unit or an isolated parameter. If neither, the results can be read from the successive nodes. The result will be cached as one node is analyzed (line 10). The form of the result comprises two components: (i) a boolean value indicating if it is a heap item; (ii) a boolean vector indicating if each generic parameter is an isolated parameter (e.g., the result of the vector  $\text{Vec}\langle T, A \rangle$  [68] is  $(1) [0, 1]$ , as shown in Figure 4).

### 4.3 Type Encoding

The encoder can analyze each field for a general type and output a bit-vector as its init rtoken (line 12). Given a type containing AdtDef and GenericArgs, the encoder first queries whether the AdtDef is already a cached heap item (line 13). If not, it will search for each isolated parameter available and verify if its GenericArg projects to a heap-item type recursively (line 16). For instance, the init rtoken of a `String` [67]  $R_{\text{String}}$  is  $[1]$ , as shown in Figure 4. Likewise, the init rtoken of the mono-morphized vector  $R_{\text{Vec}\langle u8, \text{Global} \rangle}$  is  $[1, 0]$ .

Our algorithm is efficient. The maximal time complexity of this algorithm is  $O(fd)$ , where  $f$  is the maximum field size and  $d$  is the maximum GenericArgs depth. AdtDef analysis accelerates encoding  $R_t$  via a cached hash table. It is exempt from searching in all recursive fields and for various mono-morphizations. To better support Rust features, trait objects and parameters are conservatively regarded as heap items, as shown in Table 1. At last, the init

rtokens of the pointer and reference types are always  $\vec{0}$ , and they need context from the data flow as explained in Section 5.

## 5 LEAK-FREE MODEL: FORMAL RULES

In this section, we will present a refined memory model on top of Rust MIR to check leaks across the semi-automated management boundary. This model consists of formal rules that can be applied to generate constraints through the data flow.

### 5.1 Leak-free Typed Memory Model

In general, a leak-free Rust function should satisfy the following properties:

**PROPERTY 5.1.** *There exists one and only one RAI1 token for each heap item allocated but not deallocated.*

**PROPERTY 5.2.** *Every heap item except the return value must execute `drop()` to destroy the RAI1 token before returning.*

**PROPERTY 5.3.** *The `drop()` instruction must release all necessary members (fields).*

**PROPERTY 5.4.** *The type associated with the RAI1 token is constant across statements (assignment, addressing, and dereferencing) and function calls.*

This model ensures that each heap item has a rtoken to monitor its deallocation as soon as it is constructed. Property 5.1 guarantees the exclusivity of the rtoken at each program point. Like Rust owner, rtoken is unique and can be transferred in statements and functions, but the holder is extended to reference and pointer variables. Property 5.2 dictates that each heap item must execute its destructor during its lifetime to release the resource, but it cannot guarantee that the deallocation method will free all required fields. This deficiency is remedied by Property 5.3, which improves the soundness of the Drop implementation. Noncompliance with Property 5.2 is the primary cause of orphan-object leaks, while Property 5.3 targets proxy-type issues. Property 5.4 is the constraint used to verify the pointee consistency, which will be discussed in Section 5.2.3. The refined model has the form:

$$H; M; C \vdash s \Rightarrow M'; C'$$

where  $H$  is the heap item that stores its init rtoken,  $M$  is a mapping from candidates of the rtoken holder in the current state, and  $C$  is a set of constraints. After analyzing one statement  $s$ , a new mapping  $M'$  and a new constraint set  $C'$  will be generated. This leak-free model is monotonic [49] as the bit vector becomes a semi-lattice [46].

### 5.2 Intra-procedural Rules

**5.2.1 Graph Traversal.** The analyzer is based on Rust MIR, where functions are represented as control flow graphs. The function body is a directed graph composed of basic blocks as nodes and control flow as edges. Table 2 lists the core syntax for leak detection [29, 55, 74]. `RCanary` will extract every local function inside the package, excluding dependencies, as an entry to initiate an analysis. We employ the Tarjan algorithm [20] to separate the strongly connected components (SCC) and calculate the DAG's topological order. Each SCC contains a set of nodes and may have inclusive inner SCCs

**Table 2: The core syntax of Rust MIR.**

Category	Item	Syntax	Description
Index	BasicBlock	$b \in \mathbb{Z}$	Const index of basic block started with 0.
	Local	$l \in \mathbb{Z}$	Const index of localdecl started with 0.
	Defld	$f \in \mathbb{Z}$	Internal index of function in compiler.
Variable	LocalDecl	$v \in \{v_0, v_1, \dots\}$	Variable and temporary in function.
	Type	$t \in T(P)$	Explicit type of localdecl.
	Place	$p = v[u.c][v[c]] * v$	Direct or indirect access to the localdecl.
	Operand	$o = \text{copy } p   \text{move } p$	The way of create values via loading place.
Function	Statement	$s \in STMT(b)$	Statements for function body in each block.
	Terminator	$j \in TERM(b)$	Terminator for function body in each block.
Liveness	StorageLive	$live(v)$	Mark the beginning of the live range for local.
	StorageDead	$dead(v)$	Mark the end of the live range for local.
Statement	Assignment	$p = o$	Yield the operand without changing it.
	Reference	$p = \& \_ p$	Create a reference to the place.
	AddressOf	$p = * \_ p$	Create a raw pointer to the place.
	Casting	$p = p \text{ as } t$	Cast type by using keyword "as".
	Discriminant	$disc(p, c)$	Write the discriminant for enum place.
Terminator	Goto	$goto(b)$	Jump to the successor the current block.
	Return	$return$	Return from the function.
	Drop	$drop(p, b)$	Destruct the place and go to the next block.
	Call	$call(f, p, [o], b)$	Call function: operand list and return place.

<sup>1</sup> This table only displays a subset of the syntax relevant to our paper, and the category has been modified for analysis. The full syntax can be found in RFC#1211.

due to loop nesting. Each node will analyze each statement from the top-down order, which is flow-sensitive. As shown in Figure 5, once it encounters a node with multiple predecessors, it will merge the states of all preceding nodes using  $\phi$  operation [46]. Since the  $\phi$  function is monotonic, the algorithm will iterate through each loop only once. Due to not being an iterative dataflow analysis, it is not necessary to reach the fixed point in each iteration; instead, we only emphasize the transfer of relations towards rtoken holders.

**5.2.2 Assignment Rules.** Assignments connect Place with Rvalue in MIR. `move` (explicit) and `copy` (implicit) are different semantics [23] with distinct rules. Due to space constraints, this section only briefly describes two representative rules.

**move Syntax.** The rule for move syntax is  $C_{ASGNM}$ .  $\vec{\sigma}_x, \vec{\sigma}_y$  represent the prior states, and  $\vec{\sigma}'_x, \vec{\sigma}'_y$  are the posterior states. If the rvalue carries the rtoken, the holder should be explicitly switched to the lvalue. `move` indicates that the rvalue  $x$  is no longer the holder. Thus, the constraint consists of three components: (i)  $\vec{\sigma}_y = \vec{0}$ :  $\vec{\sigma}_y$  cannot hold the rtoken. Since it will overwrite  $y$ ,  $\vec{\sigma}_y$  must not trigger leaks to satisfy Property 5.2; (ii)  $\vec{\sigma}'_x = \vec{0}$ : due to move syntax, the new state  $\vec{\sigma}'_x$  is not the holder; (iii)  $\vec{\sigma}'_y = \vec{\sigma}_x$ :  $\vec{\sigma}'_y$  will take  $\vec{\sigma}_x$ . The second and third constraints guarantee that the rtoken is exclusive by Property 5.1.

**copy Syntax.** The rule for copy syntax is  $C_{ASGNC}$ . Since the rvalue is still valid, only one of  $\vec{\sigma}'_x$  and  $\vec{\sigma}'_y$  can derive the rtoken if  $\vec{\sigma}_x$  is holding it. Otherwise, neither of them is the holder. Thus, inference for the new states  $\vec{\sigma}'_x, \vec{\sigma}'_y$  is required. The constraint consists of two parts: (i)  $\vec{\sigma}_y = \vec{0}$ : The first part is unchanged; (ii)  $\{\vec{\sigma}'_x = \vec{\sigma}_x \wedge \vec{\sigma}'_y = \vec{0}\} \vee \{\vec{\sigma}'_y = \vec{\sigma}_x \wedge \vec{\sigma}'_x = \vec{0}\}$ : The second part guarantees that the holder is exclusive and can only be distributed to  $\vec{\sigma}'_x$  or  $\vec{\sigma}'_y$ . In addition, the non-holding member must stay zeroed to satisfy Property 5.1. After adding new constraints to  $C$ , the analyzer will remap  $x, y$  to the latest state and update the mapping to  $M'$ .

**5.2.3 Pointee Consistency.** Property 5.4 is an additional constraint in our model. As demonstrated in Table 2, addressing has two distinct forms, Reference and AddressOf, which create a reference

$$\begin{array}{l}
\text{[MERGE } \phi] \quad \frac{M \vdash \forall x: \vec{\sigma}_x \quad \vec{\sigma}_x' \text{ new} \quad C' = C \wedge \{\vec{\sigma}_x' = \cap_t\}}{H; M; C \vdash \phi(x) \Rightarrow M[x \mapsto \vec{\sigma}_x']; C'} \\
\text{[RETURN]} \quad \frac{M \vdash \forall x: \vec{\sigma}_x \quad C' = C \wedge \{\vec{\sigma}_x = \vec{0}\}}{H; M; C \vdash \text{return} \Rightarrow C'} \\
\text{[ASGNM]} \quad \frac{M \vdash x: \vec{\sigma}_x, y: \vec{\sigma}_y \quad \vec{\sigma}_x', \vec{\sigma}_y' \text{ new} \quad C' = C \wedge \{\vec{\sigma}_y = \vec{0}\} \wedge \{\vec{\sigma}_x' = \vec{0}\} \wedge \{\vec{\sigma}_y' = \vec{\sigma}_x\}}{H; M; C \vdash y = \text{move } x \Rightarrow M[y \mapsto \vec{\sigma}_y', x \mapsto \vec{\sigma}_x']; C'} \\
\text{[ASGNM-READF]} \quad \frac{M \vdash x.f: \sigma_f, y: \vec{\sigma}_y \quad \sigma_f', \vec{\sigma}_y' \text{ new} \quad C' = C \wedge \{\vec{\sigma}_y = \vec{0}\} \wedge \{\sigma_f' = \vec{0}\} \wedge \{\vec{\sigma}_y' = \text{Ext}(\sigma_f)\}}{H; M; C \vdash y = \text{move } x.f \Rightarrow M[y \mapsto \sigma_f', x.f \mapsto \sigma_f']; C'} \\
\text{[ASGNM-WRITEF]} \quad \frac{M \vdash x: \vec{\sigma}_x, y.f: \sigma_f \quad \vec{\sigma}_x', \sigma_f' \text{ new} \quad C' = C \wedge \{\sigma_f = \vec{0}\} \wedge \{\vec{\sigma}_x' = \vec{0}\} \wedge \{\sigma_f = \text{SrK}(\vec{\sigma}_x)\}}{H; M; C \vdash y.f = \text{move } x \Rightarrow M[y.f \mapsto \sigma_f', x \mapsto \vec{\sigma}_x']; C'} \\
\text{[ASGNM-FTOF]} \quad \frac{M \vdash x.f: \sigma_x, y.f: \sigma_y \quad \sigma_x', \sigma_y' \text{ new} \quad C' = C \wedge \{\sigma_y = \vec{0}\} \wedge \{\sigma_x = \vec{0}\} \wedge \{\sigma_y' = \sigma_x\}}{H; M; C \vdash y.f = \text{move } x.f \Rightarrow M[y.f \mapsto \sigma_y', x.f \mapsto \sigma_x']; C'} \\
\text{[ASGNC]} \quad \frac{M \vdash x: \vec{\sigma}_x, y: \vec{\sigma}_y \quad \vec{\sigma}_x', \vec{\sigma}_y' \text{ new} \quad C' = C \wedge \{\vec{\sigma}_y = \vec{0}\} \wedge \{\vec{\sigma}_x' = \vec{\sigma}_x \wedge \vec{\sigma}_y' = \vec{0}\} \vee \{\vec{\sigma}_y' = \vec{\sigma}_x \wedge \vec{\sigma}_x' = \vec{0}\}}{H; M; C \vdash y = x \Rightarrow M[y \mapsto \vec{\sigma}_y', x \mapsto \vec{\sigma}_x']; C'} \\
\text{[ASGNC-READF]} \quad \frac{M \vdash x.f: \sigma_f, y: \vec{\sigma}_y \quad \sigma_f', \vec{\sigma}_y' \text{ new} \quad C' = C \wedge \{\vec{\sigma}_y = \vec{0}\} \wedge \{\sigma_f = \sigma_f \wedge \vec{\sigma}_y' = \vec{0}\} \vee \{\vec{\sigma}_y' = \text{Ext}(\sigma_f) \wedge \sigma_f = \vec{0}\}}{H; M; C \vdash y = x.f \Rightarrow M[y \mapsto \sigma_f', x.f \mapsto \sigma_f']; C'} \\
\text{[ASGNC-WRITEF]} \quad \frac{M \vdash x: \vec{\sigma}_x, y.f: \sigma_f \quad \vec{\sigma}_x', \sigma_f' \text{ new} \quad C' = C \wedge \{\sigma_f = \vec{0}\} \wedge \{\vec{\sigma}_x' = \vec{\sigma}_x \wedge \sigma_f' = \vec{0}\} \vee \{\sigma_f' = \text{SrK}(\vec{\sigma}_x) \wedge \vec{\sigma}_x' = \vec{0}\}}{H; M; C \vdash y.f = x \Rightarrow M[y.f \mapsto \sigma_f', x \mapsto \vec{\sigma}_x']; C'} \\
\text{[ASGNC-FTOF]} \quad \frac{M \vdash x.f: \sigma_x, y.f: \sigma_y \quad \sigma_x', \sigma_y' \text{ new} \quad C' = C \wedge \{\sigma_y = \vec{0}\} \wedge \{\sigma_x' = \sigma_x \wedge \sigma_y' = \vec{0}\} \vee \{\sigma_y' = \sigma_x \wedge \sigma_x' = \vec{0}\}}{H; M; C \vdash y.f = x.f \Rightarrow M[y.f \mapsto \sigma_y', x.f \mapsto \sigma_x']; C'}
\end{array}$$

Figure 5: The intra-procedural and field-sensitive formal rules in the leak-free memory model.

Table 3: The field primitives in the leak-free memory model.

Primitive	Description	Syntax	Operation
Ext ( $v.f$ )	read from field	$v_1 = v.f$	Sign-extend $v.f$ and meet with init rtoken.
SrK ( $v$ )	write to field	$v_1.f = v$	Join $v$ into a bit vector (length = 1).
-	field to field	$v_1.f = v.f$	No additional action.

and a raw pointer, respectively. The syntax for dereferencing operation is in PPlace item. Address types, such as  $\&\text{Vec}\langle u8 \rangle$ , represent the types of pointed places, but these types can be cast easily. Based on this prerequisite, pointee consistency restricts ambiguity among address types. Since all heap items are constructed by  $C_t$ , the type  $t$  can be inferred through context (*i.e.*, the pointee type is fixed in  $M$  and  $H$ ). As shown in Table 1, the init rtoken for address types is  $[0]$ . It cannot be the holder of any rtoken without context information. Property 5.4 simplifies the pointers by binding each variable with the fixed  $C_t$ . Therefore, it is unnecessary to distinguish between the object and address types (*i.e.*, addressing and dereferencing).

**5.2.4 Field Primitives.** The rtoken is field-sensitive. The arbitrary rtoken is a bit vector, whereas the field representation is a boolean value. Field operations may result in incompatible length issues in bit vectors for some assignments. To address them, we propose two field primitives, Ext and Srk, as listed in Table 3.

**DEFINITION 5.1.** Ext: *Extend primitive extracts rvalue’s field, sign-extends, and meets with the init rtoken of the field type.*

**DEFINITION 5.2.** Srk: *Shrink primitive joins all members from the rvalue and generates a bit vector of length one.*

Ext is only used for fields accessed via rvalues, whereas Srk is used for fields accessed via lvalues. Field primitives improve the adaptability of field operations because the lengths of the lvalue and rvalue could not be identical. Since field access is possible at any depth, we set the maximum depth to one and designated other minor accesses untracked.

## 5.3 Inter-procedural Analysis

**5.3.1 Constructor and Destructor.** Each heap item requires a constructor to initiate its lifetime. Rust provides two types of constructors: (i) the function constructor, which returns a fully initialized object, such as  $\text{Vec} : \text{new}$  [69]; (ii) the local constructor, which declares the object and initializes fields later [23]. For the local one, the initialized field can be used before the object’s full initialization. The constructor  $C_t$  and destructor  $D_t$  are defined as follows:

**DEFINITION 5.3.** *The function constructor creates init rtoken  $R_t$  via the encoder, and the local constructor creates  $\vec{0}$  with the same length as init rtoken.*

**DEFINITION 5.4.** *The destructor is the opposite of the init rtoken, namely  $\overline{R}_t$ .*

The local constructor is always initialized to zero to facilitate partial initialization. It can be updated via initialization toward fields in the data flow. For destructors executing  $\text{drop}()$ , the current rtoken will meet with a destructor rtoken to achieve deallocation. Since the destructor rtoken is  $\overline{R}_t$ , it is possible to destroy the rtoken created by the constructor. In conclusion, this model supports partial initialization, partial drop, and partial movement with field sensitivity.

**5.3.2 Inter-procedural Analysis.** Errors propagation [47] plague inter-procedural analysis that is based on boolean satisfiability. If a single incorrect constraint lies in any callee, the entire result could be UNSAT. We observed that the leaks across the semi-automated boundary have specific entries; we thus use taint analysis to simplify it; these entries are also crucial for the bug reporter. The primary components are as follows:

- The taint source consumes an object and returns `ManuallyDrop` or address-type variable.
- The taint sanitizer consumes a `ManuallyDrop` or address-type variable and returns the object with the same layout.

`Box::leak` [62] and `Box::from_raw` [61] are examples of taint sources and sanitizers, respectively. The taint source consumes the owner and returns the address-type variable; consequently, the value cannot be freed, or it will become a dangling pointer. When encountering a taint source, the code will be sent to the bug reporter as a potential leak candidate for users if the answer is UNSAT. The taint sanitizer utilizes the opposite perspective to retrieve the owner and facilitate automated allocation. In the case of functions other than taint source and sanitizer, we assume the object arguments will invoke `drop()`, while others will not be deallocated by default. The taint analysis can streamline inter-procedural analysis and reduce constraint scales. It also provides a context-sensitive inter-procedural analysis with depth options.

## 6 EVALUATION

We have built a prototype of `rCANARY`. Our implementation adds around 8k lines of Rust code to build an external component for Cargo and `rustc`. The analyzer is implemented specifically using the `rustc-v1.62` toolchain. We have conducted comprehensive evaluations of `rCANARY` using real-world Rust programs. Our evaluation aims to answer the following research questions (RQs):

- **RQ1.** How effective is `rCANARY` at detecting existing leak bugs?
- **RQ2.** How capable is `rCANARY` of finding real-world leak vulnerabilities?
- **RQ3.** How efficient is `rCANARY` in analyzing the Rust ecosystem?
- **RQ4.** How is `rCANARY` compared to other approaches?

**Experimental Setup.** The following experiments were conducted on a machine with a 2GHz Intel CPU and 32GB of RAM running 64-bit Ubuntu LTS 22.04.

### 6.1 Effectiveness Evaluation (RQ1, RQ4)

**6.1.1 Benchmark Generation.** To evaluate the effectiveness, those leak detectors will be applied to the existing buggy crates. Since `rCANARY` is the first static work aimed at Rust memory leaks across the semi-automated memory model, we have no benchmark that previously existed to evaluate. Therefore, we devised an objective benchmark containing nine crates with fixed pull requests of leak issues as the ground truth for evaluation; this benchmark can also be utilized in the subsequent study.

The generation of this benchmark rigorously follows the procedure below. We retrieve search results from GitHub using the keyword **Memory Leak**, restricting the language to Rust, and concentrating exclusively on the **Issue** and **Rull Request** sections of repositories, sorted by Github’s default order. We filter the top 30 pages of search results and exclude the following irrelevant items:

- Leaks triggered by reference counters (reference cycles).
- Leaks triggered solely by manual memory management.
- Leaks triggered outside of Rust (*i.e.*, extern FFI calls).
- Leaks referring to sensitive data leaking (*e.g.*, private key leaks).
- Repositories for Rust language teaching or learning.

After applying the above filtering criteria, the authors audit the buggy code snippet and confirm that the leaks were caused within the semi-automatic boundaries, matching the leak patterns in this paper. Finally, nine repositories are retained, as listed in Table 4.

**6.1.2 Comparing Tools.** We compare `rCANARY` to the static bug detector `FFICHECKER` [41] for Rust/C FFI, the static leak analyzer `SABER` (from SVF [70]), the runtime leak detector `LEAKSANITIZER` (from Google `ADDRESSSANITIZER` [59]), the MIR interpreter `MIRI` [28, 51], and the fuzzing tool `LIBFUZZER` (from LLVM) [58]. Because numerous static leak detectors are unsupported for Rust, we can only compare LLVM-based approaches [36].

`FFICHECKER` is built on a specific Rust version and is designed only to work for C/Rust FFI. `SABER` is a source code analyzer SVF component that employs inter-procedural sparse value-flow analysis to detect leaks in LLVM-based programming languages. Due to compatibility needs from LLVM, we modified `SABER` to conform to the allocators in Rust 1.57. The other methods mentioned are based on dynamic analysis. `LEAKSANITIZER` is a fast memory leak detector, but an executable file or unit test is required to expose vulnerabilities. Similarly, `MIRI` requires the attribute `#[text]` to annotate the unit tests. As for `LIBFUZZER`, we employ `cargo-fuzz` to activate fuzzing to buggy functions after generating fuzz targets manually. `LEAKSANITIZER`, `MIRI`, and `LIBFUZZER` are all components of Rust, so we invoke them via the Rust 1.62 toolchain.

**6.1.3 Bug Report.** `rCANARY` integrated a filter into the bug reporter to refine the output. After analyzing leak reports in the experimental phase before the evaluation, we identified the following factors that can be the root cause of irrelevant outputs: (i) **Callee Propagation:** Incorrect constraints within the callees or leaks in the callees will affect callers. (ii) **Extern Function:** Many extern functions intentionally leak resources as the return values for FFI boundaries. Thus, we devise a filter integrated into the bug reporter to filter the irrelevant items, although they trigger memory leaks. The filter only reports the taint source in the top entry and ignores the return value of extern functions if any leak exists.

**6.1.4 Results.** `rCANARY` can recall all related issues with acceptable false positives, as shown in Table 4. The number behind + indicates that the developers should manually check the FFI functions called by Rust code that can free the orphan object arguments because Rust would not deallocate them. `FFICHECKER` can detect three of them, but the limitation is that it only supports C/Rust FFI and is based on LLVM. `SABER` fails to recall any issues because its report provides no valuable information for users to locate the buggy code. The primary cause is that LLVM-IR lost high-level programming language features in Rust. `LEAKSANITIZER`, `MIRI`, and `LIBFUZZER` cannot evaluate generic functions and highly depend on the coverage of sufficient unit tests for leak functions. Furthermore, `MIRI` is insufficient for functions that invoke FFI calls. Although `rCANARY` supports analyzing functions with the `extern` keyword, it still cannot cross the FFI boundary. Since compared tools are limited in leak detection for Rust semi-automated boundaries, they have better pattern and language support than `rCANARY`.

### 6.2 Real-world Vulnerability Evaluation (RQ2)

More than 1,200 real-world Rust crates were downloaded and analyzed from `crates.io` and GitHub. All of these packages are evaluated in our experiment using a central script. For each package, the analyzer takes each local function as a distinct entry with a new context



**Table 4: Effectiveness evaluation results of rCANARY versus FFICHECKER, SABER, ASAN, MIRI, and LIBFUZZER on nine package benchmarks. These bugs are non-trivial from their pull requests (PR); the types of bugs include orphan object (OO) and proxy type (PT). The reports are classified into true positives (TF) and false positives (FP).**

Name	Package					Issue		rCANARY	FFICHECKER	SABER	ASAN	MIRI	LIBFUZZER	
	Functions	LoC	Tests	AdtDef	Ty	PR	Pattern	TP	FP	TP/FP	TP/FP	TP/FP	TP/FP	
napi-rs	1428	20.9k	14	724	2408	#1230	PT	1+18	4	0/0	0/5	FAIL	FAIL	FAIL
rust-rocksdb	3295	30.2k	43	503	1593	#658	OO	1+16	0	1/0	0/8	0/13	FAIL	1/0
arrow-rs	6164	149.6k	1202	1293	7452	#1878	OO	1+0	0	FAIL	FAIL	0/1	2/8	FAIL
arma-rs	179	2.2k	66	243	858	#22	OO	1+0	0	0/0	0/6	0/1	0/0	0/0
ruffle	6474	135.8k	915	11301	67092	#6528	PT	1+0	0	0/0	0/12	FAIL	FAIL	FAIL
flaco	22	0.4k	0	258	729	#12	PT	2+0	0	FAIL	0/3	0/0	0/0	FAIL
pprof-rs	110	2.3k	9	162	508	#84	PT	1+0	0	1/0	0/2	FAIL	0/0	1/0
rowan	406	4.4k	5	118	442	#112	PT	1+0	3	1/0	0/7	0/0	0/0	0/0
Fornjot	688	11.8k	40	304	13141	#646	PT	1+0	0	0/0	FAIL	0/0	0/0	1/0

Failed: FFICHECKER: internal errors (self abort due to panic); SABER: the minimum Rust version supported (LLVM14) conflicts with the maximum SVF support (LLVM13); ASAN: cannot integrate LEAKSANITIZER into cargo tests; MIRI: does not support to test extern FFI calls; LIBFUZZER: cannot generate fuzz targets through cargo-fuzz.

**Table 5: Real-world vulnerability evaluation results of rCANARY with the detailed issue description. After the manual check, these vulnerabilities are classified into orphan-object (OO) and proxy-type (PT), along with their leak scenarios.**

Crate	Functions	LoC	Location	Pattern	Summary	Description
basic_dsp #52	1998	30.3k	mod.rs	PT	LeakedDropImpl	Struct VectorBox<B, T> leaks the proxy field <i>argument</i> in its Drop impl.
sym synd #15	35	0.5k	cabi.rs	PT	LeakedDropImpl	Field <i>message</i> stored a boxed slice in struct CError should be freed in Drop impl.
rustfx #3	263	4.8k	core.rs*	PT	LeakedDropImpl	Proxy field <i>host</i> in struct OfxHost and <i>String</i> in enum PropertyValue.
signal-hook #150	234	5.4k	raw.rs	OO	Overwriting	Calling <i>init()</i> multiple times will leak AtomicPtr in <i>slot</i> and trigger panicking.
rust-vst2 #42	207	4.1k	host.rs	OO	Overwriting	Global LOAD_POINTER in <i>call_main()</i> will leak <i>host</i> for multiple assignments.
synthir #1	489	7.9k	emulator.rs	OO	Overwriting	MASKS_ALL and MASKS_BIT may leak the pointed Vec<BigUint>.
relibc (redox-os) #180	1709	32.0k	mod.rs*	OO	Overwriting	Calling <i>init()</i> will overwrite PTHREAD_SELF; <i>packet_data_ptr</i> may be leaked.
tinyprof #1	26	0.5k	profiler.rs	OO	Overwriting	Assign by dereferencing to PROFILER_STATE_SENDER will leak the front chunk.
tealave-sgx #441	7558	147.4k	func.rs*	OO	Overwriting	<i>session_ptr</i> and <i>p_ret_gl_config</i> may be leaked if overwrites to it.
tor_patches #1	288	4.1k	tor_log.rs	OO	Overwriting	Rewriting to LAST_LOGGED_FUNCTION and LAST_LOGGED_MESSAGE will leak box.
log #314	438	5.0k	lib.rs	OO	Finalization	<i>set_boxed_logger</i> leaks a boxed Log to LOGGER along with potential spin loop.
tracing #1517	3375	61.0k	dispatch.rs	OO	Finalization	Intentional leak towards a global GLOBAL_DISPATCH, the relevant issue in #1517.
rust-appveyor #1	43753	733.4k	thread_local.rs	OO	Finalization	KEYS and LOCALS need finalization function to clean up.
ServoWsgi	11606	236.2k	opts.rs	OO	Lazy	DEFAULT_OPTIONS needs finalization to clean up, especially for multi threads exit.
ruX	585	9.9k	lazy.rs	OO	Lazy	The current lazy static uses the ' <i>static</i> ' that cannot be freed in multi threads.
next_space_coop	20477	317.1k	lazy.rs	OO	Lazy	The current lazy static uses the ' <i>static</i> ' that cannot be freed in multi threads.
rio #52	95	3.0k	lazy.rs	OO	PanicPath	If the assertion goes into unwinding, the <i>value</i> will be leaked inside a panic.
sled #1458	1350	32.8k	lazy.rs	OO	PanicPath	If the assertion goes into unwinding, the <i>value</i> will be leaked inside a panic.

The item having \* indicates vulnerabilities located in multiple files. Additionally, we did not open an issue specifically for scenario Lazy, due to it being a common design flaw in lazy\_static implementations.

and checks the leak-free memory model to detect potential leaks in their function bodies.

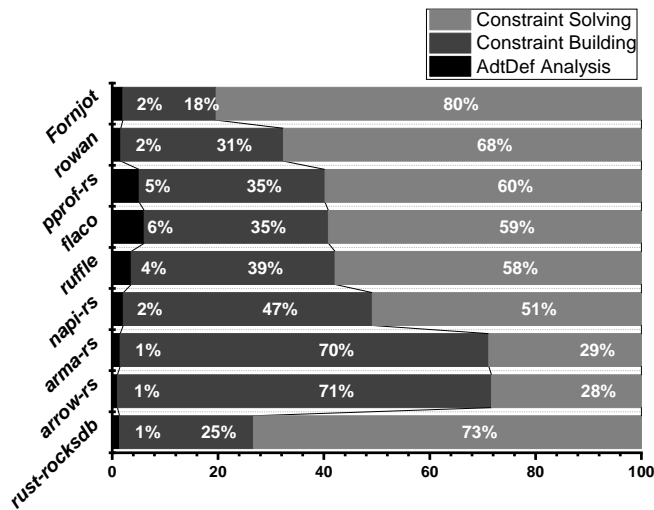
Among the evaluated packages, 3.0% have conflicted with the Rust version after switching to our toolchain, 11.6% have an unsupported virtual Cargo workspace, and 85.4% have been effectively analyzed by rCANARY. After diagnostic messages are sent to the bug reporter, we manually check the source code and categorize them based on leak patterns and real-world programming scenarios. The report outputs the vulnerabilities with related code locations and further pinpoints the detailed leak object lists.

We listed 19 crates with potential leaks, and the detailed descriptions are listed in Table 5. Those vulnerabilities are non-trivial and have different scenarios. For example, the orphan-object leak in the popular crate `signal-hook` from crates.io exposes the problem of repeated assignment to a static mut pointer, causing a local thread leak. The proxy-type vulnerabilities in `basic_dsp` have generic-type parameters invisible for dynamic tests without

mono-morphization. We observe that the reassignment of the static pointer is error-prone to memory leaks, which will be discussed in the case study.

### 6.3 Performance Evaluation (RQ3)

We expect rCANARY to be an efficient static scanner for the Rust ecosystem. It should not impose significant overhead on the target package. At the ecosystem scale, rCANARY took about 96 minutes to scan 1.2k real-world Rust packages. It took 8.4 seconds on average to analyze each package. Since we use incremental compilation, it does contain the overhead of the local compilation elapsed. Besides, there was no aborting or self-panicking while running our analyzer on all evaluated crates. That indicates rCANARY is promising to be a general, reliable, and fast source-code leak scanner for the Rust ecosystem.



**Figure 6: The time distribution results of rCANARY on the benchmark. For the virtual workspace, we individually test each crate inside and calculate the average percentage distribution in three phases.**

We further examine the analysis time distribution among three phases toward our benchmarks, as shown in Table 4. All experiments were repeated five times. For each package, the one-round time cost can be divided into AdtDef analysis, constraint building, and constraint solving. The median distributions are AdtDef analysis at 5%, constraint building at 35%, and constraint solving at 59%. The algorithm of AdtDef analysis is efficient, and the constraint-related phases cost most of the analysis time (more than 95%). The cost of constraint building and constraint solving does not illustrate explicit relevance because the front one contains type encoding for variables and suffers from macros expansion due to generating massive types that may drag down the speed (e.g., the count of types in `ruffie`). As our algorithm is not capable of pointer arithmetics, thus the solver may be accelerated if those operations are wildly used (e.g., `arma-rs`).

## 6.4 Case Study

As static variables are represented as normal locals (variables) in MIR, we did not initially consider their peculiarities when designing rCANARY. However, real-world vulnerabilities have revealed specific issues. Many programmers use `static mut` values to store global data on the heap, but numeral implementations are unsound, including:

- Unsound init functions that can overwrite and leak the previously stored value, potentially leading to denial-of-service attacks or memory exhaustion.
- Static variables that are thread-unsafe or non-finalizing, including `static mut` and lazy values, which cannot be deallocated when threads exit.
- Incapability to deal with the poisoned static variables if the first initialization panics.

This work provided the Rust and SE communities with a hint. Currently, three primary uses may be error-prone to leaks in semi-automatic memory management:

- Orphan objects (containing proxy fields) that have been neglected to be released in Rust.
- Orphan objects leaked outside Rust in the extern FFI calls.
- Thread-unsafe and unsound use of global variables on the heap.

## 6.5 Discussion

**Limitations.** Like most static leak detectors, rCANARY is neither sound nor complete. The heap-item unit hinges on phantom data in the encoder. This convention can cover all std collection types but may result in false positives for seldom user-defined types. And the access depth of fields is restricted in our model. The field primitives optimize the result but still cannot eliminate false negatives. At last, our algorithm does not support pointer arithmetic.

**Future Work.** After studying the leak cases and auditing the buggy code from rCANARY’s reports, we discovered that the boundary between automated and manual deallocation is still unclear in FFI scenarios. We are now dedicated to promoting a new RFC to prevent leaks across the semi-automated boundary. It designs a pointer wrapper like `ManuallyDrop` with a set of new APIs and an explicit annotation for external function signatures to downcast the owner identity for pointers and perform automated deallocation for them.

## 7 RELATED WORK

**Ownership model.** Our work is based on the Rust ownership system and adds a series of formal rules. Leak-free memory model shares many similarities with ownership syntax [11, 26], and C++ smart pointers [18]. Our work resembles linear types [21, 72] to support Rust syntax features such as moving ownership [53]. Clarke et al. [26] proposed a strict ownership model named ownership type that asserts the owning relation between objects [13, 50]. Clouseau [26] adds the features of ownership transfer, arbitrary aliases, and ownership invariant at function boundaries to enhance scalability, which is one of the foundations of our model. Although some language extensions are proposed to allow read-only aliases [8, 73], the strict definition does not require right-hand-side pointers [72]. Our model allows pointers to access objects, but the holder of the RAI token must be exclusive [7, 12]. It also extends the proprietor to all pointer types and provides an explicit boundary between stack-allocated and heap-allocated data.

**Static leak detection.** Numerous studies focus on detecting leaks using static analysis. FFICHECKER [41] is designed for Rust based on LLVM but only supports C FFI. Saturn [75] is based on boolean satisfiability, which is context- and path-sensitive. rCANARY, unlike Saturn, is a path-insensitive but flow-sensitive model checker. Clouseau [26] is a flow- and context-sensitive ownership model, but our work has a field-sensitive data abstraction. It is more complex and provides features like partial initialization and partial deallocation. Some studies employ symbolic execution [31] and abstract interpretation [15, 16] to detect leaks in C programs such as KLEE [9], Clang [35], and Sparrow [30]. Also, the full-sparse value-flow analysis [25, 70, 71] monitors value flow and define-use chains via top-level and address-taken pointers to detect leaks. Like SVF,

semi-sparse flow-sensitive analysis [10, 24] can identify define-use chains by explicitly placing top-level pointers in SSA form.

## 8 CONCLUSION

Semi-automated memory management still causes memory leaks in Rust programs. In this paper, we studied and summarized leak patterns caused by semi-automated memory management, then presented rCANARY, a static, non-intrusive, and fully automated model checker based on boolean satisfiability to detect them. We implemented rCANARY on top of Rust MIR and evaluated it through real-world Rust packages. rCANARY can efficiently recall our benchmarks and find 19 crates with potentially vulnerable leaks.

## REFERENCES

- [1] Brian Anderson, Lars Bergstrom, Manish Goregaokar, Josh Matthews, Keegan McAllister, Jack Moffitt, and Simon Sapin. 2016. Engineering the servo web browser engine using Rust. In *Proceedings of the 38th International Conference on Software Engineering Companion*. 81–89. doi:10.1145/2889160.2889229.
- [2] Andrew W Appel. 1998. SSA is functional programming. *Acm Sigplan Notices* 33, 4 (1998), 17–20. doi:10.1145/278283.278285.
- [3] arXiv. 2023. Is unsafe an Achilles' Heel? A Comprehensive Study of Safety Requirements in Unsafe Rust Programming. In *arXiv*.
- [4] Vytautas Astrauskas, Christoph Matheja, Federico Poli, Peter Müller, and Alexander J Summers. 2020. How do programmers use unsafe rust? *Proceedings of the ACM on Programming Languages* 4, OOPSLA (2020), 1–27. doi:10.1145/3428204.
- [5] Yechan Bae, Youngsuk Kim, Ammar Askar, Jungwon Lim, and Taesoo Kim. 2021. Rudra: finding memory safety bugs in rust at the ecosystem scale. In *Proceedings of the ACM SIGOPS 28th Symposium on Operating Systems Principles*. 84–99. doi:10.1145/3477132.3483570.
- [6] Abhiram Balasubramanian, Marek S Baranowski, Anton Burtsev, Aurojit Panda, Zvonimir Rakamarić, and Leonid Ryzhik. 2017. System programming in rust: Beyond safety. In *Proceedings of the 16th Workshop on Hot Topics in Operating Systems*. 156–161. doi:10.1145/3102980.3103006.
- [7] Chandrasekhar Boyapati, Robert Lee, and Martin Rinard. 2002. Ownership types for safe programming: Preventing data races and deadlocks. In *Proceedings of the 17th ACM SIGPLAN conference on Object-oriented programming, systems, languages, and applications*. 211–230. doi:10.1145/582419.582440.
- [8] John Boyland. 2001. Alias burying: Unique variables without destructive reads. *Software: Practice and Experience* 31, 6 (2001), 533–553. doi:10.1002/spe.370.
- [9] Cristian Cadar, Daniel Dunbar, Dawson R Engler, et al. 2008. Klee: unassisted and automatic generation of high-coverage tests for complex systems programs.. In *OSDI*, Vol. 8. 209–224. [https://www.usenix.org/legacy/event/osdi08/tech/full\\_papers/cadar/cadar.pdf](https://www.usenix.org/legacy/event/osdi08/tech/full_papers/cadar/cadar.pdf)
- [10] Sigmund Cherm, Lonnie Princehouse, and Radu Rugina. 2007. Practical memory leak detection using guarded value-flow analysis. In *Proceedings of the 28th ACM SIGPLAN Conference on Programming Language Design and Implementation*. 480–491. doi:10.1145/1250734.1250789.
- [11] Davis Clarke. 2001. An object calculus with ownership and containment. (2001). <https://courses.cs.washington.edu/courses/cse590p/01wi/clarke-fool8.pdf>
- [12] Dave Clarke and Sophia Drossopoulou. 2002. Ownership, encapsulation and the disjointness of type and effect. In *Proceedings of the 17th ACM SIGPLAN conference on Object-oriented programming, systems, languages, and applications*. 292–310. doi:10.1145/582419.582447.
- [13] David G Clarke, John M Potter, and James Noble. 1998. Ownership types for flexible alias protection. In *Proceedings of the 13th ACM SIGPLAN conference on Object-oriented programming, systems, languages, and applications*. 48–64. doi:10.1145/286936.286947.
- [14] CWE-400: Uncontrolled Resource Consumption. 2023. [ehttps://cwe.mitre.org/data/definitions/400.html](https://cwe.mitre.org/data/definitions/400.html) (Accessed on 07/25/2023).
- [15] Patrick Cousot and Radhia Cousot. 1977. Abstract interpretation: a unified lattice model for static analysis of programs by construction or approximation of fixpoints. In *Proceedings of the 4th ACM SIGACT-SIGPLAN symposium on Principles of programming languages*. 238–252. doi:10.1145/512950.512973.
- [16] Patrick Cousot and Radhia Cousot. 1979. Systematic design of program analysis frameworks. In *Proceedings of the 6th ACM SIGACT-SIGPLAN symposium on Principles of programming languages*. 269–282. doi:10.1145/567752.567778.
- [17] Mohan Cui, Chengjun Chen, Hui Xu, and Yangfan Zhou. 2023. SafeDrop: Detecting memory deallocation bugs of rust programs via static data-flow analysis. *ACM Transactions on Software Engineering and Methodology* 32, 4 (2023), 1–21. doi:10.1145/3542948.
- [18] Daniel Edelson and I Pohl. 1992. *Smart pointers: They're smart, but they're not pointers*. Citeseer. <https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=d78dd0f23e9c75b4841111b1978c2997d9965c18>
- [19] Ana Nora Evans, Bradford Campbell, and Mary Lou Soffa. 2020. Is Rust used safely by software developers?. In *Proceedings of the ACM/IEEE 42nd International Conference on Software Engineering*. 246–257. doi:10.1145/3377811.3380413.
- [20] Harold N. Gabow and Robert Endre Tarjan. 1983. A Linear-Time Algorithm for a Special Case of Disjoint Set Union. In *Proceedings of the Fifteenth Annual ACM Symposium on Theory of Computing (STOC '83)*. Association for Computing Machinery. doi:10.1145/800061.808753.
- [21] Jean-Yves Girard. 1995. Linear logic: its syntax and semantics. *London Mathematical Society Lecture Note Series* (1995), 1–42.
- [22] Rust Group. 2023. The Rust community's crate registry. <https://crates.io> (Accessed on 07/25/2023).
- [23] Rust Group. 2023. The Rust Reference. <https://doc.rust-lang.org/reference> (Accessed on 07/25/2023).
- [24] Ben Hardekopf and Calvin Lin. 2009. Semi-sparse flow-sensitive pointer analysis. *ACM SIGPLAN Notices* 44, 1 (2009), 226–238. doi:10.1145/1594834.1480911.
- [25] Ben Hardekopf and Calvin Lin. 2011. Flow-sensitive pointer analysis for millions of lines of code. In *International Symposium on Code Generation and Optimization (CGO 2011)*. IEEE, 289–298. doi:10.1109/CGO.2011.5764696.
- [26] David L Heine and Monica S Lam. 2003. A practical flow-sensitive and context-sensitive C and C++ memory leak detector. In *Proceedings of the ACM SIGPLAN 2003 conference on Programming language design and implementation*. 168–181. doi:10.1145/781131.781150.
- [27] Michael Hicks, Greg Morrisett, Dan Grossman, and Trevor Jim. 2004. Experience with safe manual memory-management in Cyclone. In *Proceedings of the 4th international symposium on Memory management*. 73–84. doi:10.1145/1029873.1029883.
- [28] Ralf Jung, Hoang-Hai Dang, Jeehoon Kang, and Derek Dreyer. 2019. Stacked borrows: an aliasing model for Rust. *Proceedings of the ACM on Programming Languages* 4, POPL (2019), 1–32. doi:10.1145/3371109.
- [29] Ralf Jung, Jacques-Henri Jourdan, Robbert Krebbers, and Derek Dreyer. 2017. Rust-Belt: Securing the foundations of the Rust programming language. *Proceedings of the ACM on Programming Languages* 2, POPL (2017), 1–34. doi:10.1145/3158154.
- [30] Yungbum Jung and Kwangkeun Yi. 2008. Practical memory leak detector based on parameterized procedural summaries. In *Proceedings of the 7th international symposium on Memory management*. 131–140. doi:10.1145/1375634.1375653.
- [31] James C King. 1976. Symbolic execution and program testing. *Commun. ACM* 19, 7 (1976), 385–394. doi:10.1145/360248.360252.
- [32] Steve Klambnik and Carol Nichols. 2019. *The Rust Programming Language (Covers Rust 2018)*. No Starch Press.
- [33] Rust lang Group. 2015. Unsafe intrinsic mem::forget in Rust release version 0.12. <https://github.com/rust-lang/rust/blob/ba4081a5a8573875fed17545846f6902c8ba8d/src/libcore/intrinsics.rs#L302> (Accessed on 07/25/2023). (2015).
- [34] Stefan Lankes, Jens Breitbart, and Simon Pickartz. 2019. Exploring rust for unikernel development. In *Proceedings of the 10th Workshop on Programming Languages and Operating Systems*. 8–15. doi:10.1145/3365137.3365395.
- [35] Chris Lattner. 2008. LLVM and Clang: Next generation compiler technology. In *The BSD conference*, Vol. 5. 1–20. [https://reup.dmcsl.pl/wiki/images/0/09/53\\_BSDCan2008ChrisLattnerBSDCompiler.pdf](https://reup.dmcsl.pl/wiki/images/0/09/53_BSDCan2008ChrisLattnerBSDCompiler.pdf)
- [36] Chris Lattner and Vikram Adve. 2004. LLVM: A compilation framework for lifelong program analysis & transformation. In *International Symposium on Code Generation and Optimization, 2004. CGO 2004*. IEEE, 75–86. doi:10.1109/CGO.2004.1281665.
- [37] Amit Levy, Michael P Andersen, Bradford Campbell, David Culler, Prabal Dutta, Branden Ghena, Philip Levis, and Pat Pannuto. 2015. Ownership is theft: Experiences building an embedded OS in Rust. In *Proceedings of the 8th Workshop on Programming Languages and Operating Systems*. 21–26. doi:10.1145/2818302.2818306.
- [38] Amit Levy, Bradford Campbell, Branden Ghena, Daniel B Giffin, Shane Leonard, Pat Pannuto, Prabal Dutta, and Philip Levis. 2017. The tock embedded operating system. In *Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems*. 1–2. doi:10.1145/3131672.3136988.
- [39] Amit Levy, Bradford Campbell, Branden Ghena, Daniel B Giffin, Pat Pannuto, Prabal Dutta, and Philip Levis. 2017. Multiprogramming a 64kb computer safely and efficiently. In *Proceedings of the 26th Symposium on Operating Systems Principles*. 234–251. doi:10.1145/3132747.3132786.
- [40] Zhuohua Li, Jincheng Wang, Mingshen Sun, and John CS Lui. 2021. MirChecker: detecting bugs in Rust programs via static analysis. In *Proceedings of the 2021 ACM SIGSAC Conference on Computer and Communications Security*. 2183–2196. doi:10.1145/3460120.3484541.
- [41] Zhuohua Li, Jincheng Wang, Mingshen Sun, and John CS Lui. 2022. Detecting cross-language memory management issues in rust. In *European Symposium on Research in Computer Security*. Springer, 680–700. doi:10.1007/978-3-031-17143-7\_33.
- [42] Yuanzhi Liang, Lei Wang, Siran Li, and Bo Jiang. 2021. Rustpi: A Rust-powered Reliable Micro-kernel Operating System. In *2021 IEEE International Symposium on Software Reliability Engineering Workshops (ISSREW)*. IEEE, 272–273. doi:10.1109/ISSREW53611.2021.00075.

- [43] SMT-LIB: THE SATISFIABILITY MODULO THEORIES LIBRARY. 2023. <http://smtlib.cs.uiowa.edu/> (Accessed on 07/25/2023).
- [44] Alex Light. 2015. Reenix: Implementing a unix-like operating system in rust. *Undergraduate Honors Theses, Brown University* (2015). <https://api.semanticscholar.org/CorpusID:18213575>
- [45] Nicholas D Matsakis and Felix S Klock. 2014. The rust language. *ACM SIGAda Ada Letters* 34, 3 (2014), 103–104. doi:10.1145/2692956.2663188.
- [46] Anders Møller and Michael I Schwartzbach. 2012. Static program analysis. *Notes. Feb* (2012).
- [47] Leonardo de Moura and Nikolaj Bjørner. 2008. Z3: An efficient SMT solver. In *International conference on Tools and Algorithms for the Construction and Analysis of Systems*. Springer, 337–340. [https://link.springer.com/chapter/10.1007/978-3-540-78800-3\\_24](https://link.springer.com/chapter/10.1007/978-3-540-78800-3_24)
- [48] Santosh Nagarakatte, Milo MK Martin, and Steve Zdancewic. 2012. Watchdog: Hardware for safe and secure manual memory management and full memory safety. In *2012 39th Annual International Symposium on Computer Architecture (ISCA)*. IEEE, 189–200. doi:10.1145/2366231.2337181.
- [49] Flemming Nielson, Hanne R Nielson, and Chris Hankin. 2004. *Principles of program analysis*. Springer Science & Business Media.
- [50] James Noble, Jan Vitek, and John Potter. 1998. Flexible alias protection. In *European Conference on Object-Oriented Programming*. Springer, 158–185. <https://link.springer.com/chapter/10.1007/BFb0054091>
- [51] S Olson. 2016. *Miri: an interpreter for Rust's mid-level intermediate representation*. Technical Report. Technical report. <https://solson.me/miri-report.pdf>
- [52] Maksim Orlovich and Radu Rugina. 2006. Memory leak analysis by contradiction. In *International Static Analysis Symposium*. Springer, 405–424. doi:10.1007/11823230\_26.
- [53] Benjamin C Pierce. 2004. *Advanced topics in types and programming languages*. MIT press.
- [54] RedoxOS. [n.d.]. RedoxOS Contributors. 2022., <https://www.redox-os.org/>.
- [55] Eric Reed. 2015. Patina: A formalization of the Rust programming language. *University of Washington, Department of Computer Science and Engineering, Tech. Rep. UW-CSE-15-03-02* (2015), 264. <https://api.semanticscholar.org/CorpusID:10124530>
- [56] rustc\_middle::ty::adt::AdtDef. 2023. [https://doc.rust-lang.org/nightly/nightly-rustc/rustc\\_middle/ty/adt/struct.AdtDef.html](https://doc.rust-lang.org/nightly/nightly-rustc/rustc_middle/ty/adt/struct.AdtDef.html) (Accessed on 07/25/2023).
- [57] rustc\_middle::ty::generic\_args::GenericArgs. 2023. [https://doc.rust-lang.org/nightly/nightly-rustc/rustc\\_middle/ty/generic\\_args/type.GenericArgs.html](https://doc.rust-lang.org/nightly/nightly-rustc/rustc_middle/ty/generic_args/type.GenericArgs.html) (Accessed on 07/25/2023).
- [58] Kosta Serebryany. 2016. Continuous fuzzing with libfuzzer and address-sanitizer. In *2016 IEEE Cybersecurity Development (SecDev)*. IEEE, 157–157. doi:10.1109/SecDev.2016.043.
- [59] Konstantin Serebryany, Derek Bruening, Alexander Potapenko, and Dmitriy Vyukov. 2012. {AddressSanitizer}: A Fast Address Sanity Checker. In *2012 USENIX Annual Technical Conference (USENIX ATC 12)*. 309–318. <https://www.usenix.org/conference/atc12/technical-sessions/presentation/serebryany>
- [60] Youren Shen, Hongliang Tian, Yu Chen, Kang Chen, Runji Wang, Yi Xu, Yubin Xia, and Shoumeng Yan. 2020. Occlum: Secure and efficient multitasking inside a single enclave of intel sgx. In *Proceedings of the Twenty-Fifth International Conference on Architectural Support for Programming Languages and Operating Systems*. 955–970. doi:10.1145/3373376.3378469.
- [61] std::boxed::Box::from\_raw. 2023. [https://doc.rust-lang.org/std/boxed/struct.Box.html#method.from\\_raw](https://doc.rust-lang.org/std/boxed/struct.Box.html#method.from_raw) (Accessed on 07/25/2023).
- [62] std::boxed::Box::leak. 2023. <https://doc.rust-lang.org/std/boxed/struct.Box.html#method.leak> (Accessed on 07/25/2023).
- [63] std::marker::PhantomData. 2023. <https://doc.rust-lang.org/std/marker/struct.PhantomData.html> (Accessed on 07/25/2023).
- [64] std::mem::ManuallyDrop. 2023. <https://doc.rust-lang.org/std/mem/struct.ManuallyDrop.html> (Accessed on 07/25/2023).
- [65] std::ops::Drop. 2023. <https://doc.rust-lang.org/std/ops/trait.Drop.html> (Accessed on 07/25/2023).
- [66] std::ptr::drop\_in\_place. 2023. [https://doc.rust-lang.org/std/ptr/fn.drop\\_in\\_place.html](https://doc.rust-lang.org/std/ptr/fn.drop_in_place.html) (Accessed on 07/25/2023).
- [67] std::string::String. 2023. <https://doc.rust-lang.org/std/string/struct.String.html> (Accessed on 07/25/2023).
- [68] std::vec::Vec. 2023. <https://doc.rust-lang.org/std/vec/struct.Vec.html> (Accessed on 07/25/2023).
- [69] std::vec::Vec::new. 2023. <https://doc.rust-lang.org/std/vec/struct.Vec.html#method.new> (Accessed on 07/25/2023).
- [70] Yulei Sui and Jingling Xue. 2016. SVF: interprocedural static value-flow analysis in LLVM. In *Proceedings of the 25th international conference on compiler construction*. 265–266. doi:10.1145/2892208.2892235.
- [71] Yulei Sui, Ding Ye, and Jingling Xue. 2014. Detecting memory leaks statically with full-sparse value-flow analysis. *IEEE Transactions on Software Engineering* 40, 2 (2014), 107–122. doi:10.1109/TSE.2014.2302311.
- [72] Philip Wadler. 1990. Linear types can change the world!. In *Programming concepts and methods*, Vol. 3. Citeseer, 5. <https://api.semanticscholar.org/CorpusID:58535510>
- [73] David Walker and Greg Morrisett. 2000. Alias types for recursive data structures. In *International Workshop on Types in Compilation*. Springer, 177–206. [https://link.springer.com/chapter/10.1007/3-540-45332-6\\_7](https://link.springer.com/chapter/10.1007/3-540-45332-6_7)
- [74] Feng Wang, Fu Song, Min Zhang, Xiaoran Zhu, and Jun Zhang. 2018. Krust: A formal executable semantics of rust. In *2018 International Symposium on Theoretical Aspects of Software Engineering (TASE)*. IEEE, 44–51. doi:10.1109/TASE.2018.00014.
- [75] Yichen Xie and Alex Aiken. 2005. Context-and path-sensitive memory leak detection. In *Proceedings of the 10th European software engineering conference held jointly with 13th ACM SIGSOFT international symposium on Foundations of software engineering*. 115–125. doi:10.1145/1081706.1081728.