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Paper title

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Kapitel 1

Outline

1. Introduction
2. Motivation
3. Review of similar solutions
4. Methodology
5. Implementation
6. Evaluation
7. Conclusion
8. Future work

Kapitel 2

Introduction

- Rust is increasing usage in system level
- but still many big projects (linux etc.) are written in C

2.1 Rust

2.2 FUSE

[1]

Kapitel 3
Motivation

Since the beginning of programming, there has been a discrepancy between the input states an interface formally accepts, and the input states that are sound to handle. For example, a reciprocal function $f(x) = 1/x$ might formally accept a 32 bit integer — and therefore all of its $2 ^ 32$ input states —, but the mathematical formula it tries to model will not give a sensible result for $x = 0$; least of all if the function in turn returns an integer, since there is no integer $n: 1 / x = n$.

One straightforward solution has always been to limit the function domain via documentation. Users of that function are expected to read that documentation and recognize that it is a violation of interface contract to call it with $x = 0$. Violation of that contract would in turn result in an error, a crash, or — worse yet — Undefined Behaviour. An approach with drawbacks, as there are now two sources of truth about the function domain. One of these — the function signature, expressed in code — is already technically incorrect, as we have not stated a way to express "integers without zero" as a valid type. Additionally, as the program developes, the chance of both sources of truth to get further out-of-sync increases. This discrepancy,between the high-level contract, expressible only in additional information in text form, and the function signature the compiler handles, raises the following question: Can we encode this precondition in such a way that the function signature makes it impossible to pass in values that violate any API contract?

In languages where we have strict and strong typing , we can enforce invariants about types we create, since we have to explicitly provide the methods of construction for these types, and we can make then fail if some invariants are not upheld. This allows us to express function signatures of the kind discussed previously, by creating a new type `NonZeroI32`Listing 1 that represents the idea of an integer that cannot be zero. By making the inner value private, we then ensure that users of our library are forced to use the only construction method we provide them with, `NonZeroI32::new(i32)`. This `new()` function can be total, since it returns a result value representing a fallible computation. In that sense, the function signature of `new()` expresses that **every 32-bit integer is either a valid non-zero 32-bit integer or an error**.

```rust
pub struct NonZeroI32(i32);

impl NonZeroI32 {
  pub fn new(n: i32) -> Result<Self> {
    if n == 0 {
      Err("n == 0 is not allowed!")
    } else {
      Ok(n)
    }
  }
}

pub fn reciprocal(n: NonZeroI32) -> NonZeroI32 {
  // ...
}
```

Listing 1: A new type `NonZeroI32` that represents the idea of a 32-bit integer **guaranteed** to not be zero

Kapitel 4

Review of similar solutions

- rust-fatfs
- fuser
    - auch in rust
    - fuse LowLevel statt “normal” API (mine)
    - **aber**: verwendet eh niemand
- rust in linux kernel

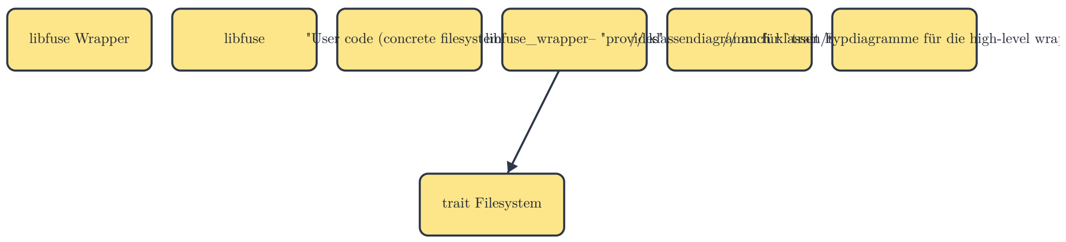
Kapitel 5
Concept

[2], [3], [4], [5], [6]

- read similar rust projects, get idea about how the structure and approach would look for the libfuse bindings
- read up about `cbindgen` by mozilla (will def. need to use it)
- read up about theoretical foundation of type systems and using them to encode programmer contracts
- for every libfuse API call:
  - decide if in-scope
  - enumerate a list of (sensible) contracts
  - encode through type system
    - if that fails or becomes too hard, skip them and document that
- (if possible) collect filesystem related CVEs from databases
- (else) CWEs allgemein sammeln
- match CVEs/CWEs with libfuse calls, find potential weaknesses/threads
- evaluate if my rust constructs can fix those weaknesses. if not, try to improve bindings.
- create stats and tables (e.g. percentage CVEs prevented, taken from a) sub section X, b) time span Y, etc.)
- write introduction with foundational concepts

Kapitel 6

Implementation



6.1 Basic C interop

6.1.1 Pointers

- for every C pointer we have to use
  - is it aligned?
  - is it non-null?
  - (is it valid? not checkable without allocator control or sanitizer or sim.)

6.1.2 Strings and Unicode

- rust only allows UTF-8 Strings
- although there are wrappers for C-style strings, most APIs are built to only work on Unicode
- => we disallow non-UTF-8 strings for simplicity

6.1.3 Panics across FFI boundaries

- => is UB
- have to wrap every possible panic point inside `catch_unwind()`
- not provably panic-free with just compiler

    - but there is an interesting crate: `https://github.com/dtolnay/no-panic` => **future work**

6.2 FUSE operations

- these 4 functions seem to be the bare minimum for a R/O filesystem (see libfuse example `hello`)
- open can be a noop

6.2.1 getattr

- “bread and butter” call, is the first one executed on all filesystem paths, lets user decide how to continue (readdir on dirs, read/open on files e.g.)
-

6.2.2 readdir

6.2.3 open

6.2.4 read

6.3 Initialization / global state management

- We need to supply a number of C functions that know which user impl to call
- Possibility: just use data pointer from `libfuse::init`
    - Con: push raw pointers around, prone to corruption
- My choice: use generics, overload generic trampolines with user Filesystem type
    - that way, the compiler generates a concrete version (with its own address and hard-coded user code address) of our generic trampolines
    - since generic parameter is the only type with `impl Filesystem` in scope, type system prevents any confusion/programmer error.
    - since compiler generates hardcoded version, memory corruption due to logic errors anywhere is also not a problem
    - con: only one instance per struct type per process.
        - workaround: just use wrapper structs (can be done easily from user code)

Since the libfuse initialization routine takes a struct of callback function pointers (`fuse_ops`), that creates the following problem. Since the C signature is predetermined, user functions cannot be used, because that would force signatures of user functions to use the lower-level C types which we try to avoid. That means, even though there is a one-to-one correspondence between FUSE operation callbacks and trait methods on the `Filesystem` trait, they are not compatible and cannot be used interchangably. The obvious approach is to provide trampoline functions (trampoline_functions), which then wrap, transform and safety-check the C type values on call and dispatch into user code. A non-trivial problem, that is not obvious at first sight, is how the trampoline knows which filesystem implementation to dispatch to. There are two basic options how to use the trampolines:

1. use one global trampoline per callback, and somehow transport the choice on which filesystem to use inside the C arguments that the libfuse wrapper (libfuse_wrapper) gets passed by TODO libfuse (libfuse).
2. somehow generate a set of trampolines per user filesystem, which are then hard-coded towards the specific filesystem implementation.

A way to implement option 1 is provided in the form of a `void *private_data` pointer that can be passed to libfuse during filesystem registration. This pointer can contain arbitrary user-specified data, and is not used by libfuse except for making it available to every fuse operation via the `fuse_get_context`[1] function.

Since it is possible to store a Rust pointer inside a C void pointer, libfuse_wrapper can submit a pointer to the user implementation as payload for `private_data`, then let each trampoline poll the FUSE context struct, cast the void pointer back to a trait object reference and dispatch into the corresponding trait method. This has the following disadvantages:

- Decaying a managed Rust reference into a raw pointer loses the advantage of lifetime tracking that is one of Rusts fortes in the undertaking of creating safe systems-level code. Manual care has to be taken not to invoke a use-after-free, accessing an uninitialized or unauthorized memory location or — in the best case — simply leaking memory. In fact, the safest option would be to initialize this data pointer once, and then never free it, since it is the dealloc part that introduces memory unsafety to a system , and even if leaking memory (and not calling destructors) is acceptable, since libfuse passes around non-const pointers to everything, bugs at any point of both our trampolines and libfuse can easily lead to access of corrupted pointers and therefore to UB. This is usually a tradeoff that must be accepted when dealing with FFI into unsafe languages, but should be mitigated whenever feasible.

Both disadvantages would in theory prevented by a solution after option 2, and thankfully, with the use of generics, Rust brings includes the tools to implement such a solution. As seen in Listing 2, this exemplary trampoline function is generic over types implementing our `Filesystem` trait. This leads the Rust compiler to generate a concrete, independent `getattr` trampoline function for every trait implementation of `Filesystem` that is used to call our initialization function. The generic approach is then combined with a singleton registry[2] which provides a global map of values, indexed

[1] https://libfuse.github.io/doxygen/fuse_8h.html#a5fce94a5343884568736b6e0e2855b0e
[2] https://crates.io/crates/singleton-registry

by types. We can now store the concrete user-supplied filesystem struct inside this registry and use the type of this filesystem struct as index, which additionally will be deduced implicitly by the compiler from the argument types of our initialization function. That means, given there are no other implemenations of our `Filesystem` trait in scope when declaring the generic functions, the type system guarantees us that the user's type is the only one that can be used for dispatching, shielding even against potential programmer oversight.

This has the drawback of only allowing one instance of a concrete `Filesystem` type to be mounted per process. But since — if needed — newtype structs (newtype_structs) can be used to create different concrete types with minimal boilerplate, this was deemed tolerable.

```
pub unsafe extern "C" fn getattr<FS: Filesystem>(
    path: *const i8,
    stat_out: *mut libfuse::stat,
    _fuse_file_info_out: *mut libfuse::fuse_file_info,
) -> i32 {
```
Listing 2: An exemplary trampoline function signature implementing compile-time static dispatch via generics

6.4 Type modeling

6.4.1 `stat`

- gives basic info about FS entry
- returned by getattr
-

6.4.2 `fuse_file_info`

6.4.3 FileMode

6.4.3.1 Typed builder

- question: how do I model type creation?
    - free function: no named parameters, gets unreadable quickly, no optional parameters
    - struct init: grundsätzlich recht sicher, aber
        - pro: parameter sind benannt
        - manche felder mandatory, manche optional: geht nicht
        - struct muss default trait implementieren, dann sind alle felder basically optional, und es ist möglich, potentiell invalide objekte zu erstellen
        - keine schicken auto-converts und transformations, bounds checking etc.

    - “normal” runtime builder
        - pro: sehr flexibel, ergonomisch
        - con: wird ein mandatory feld vergessen, gibts erst zur runtime nen fehler
    - typed builder:
        - pro: flexibilität und mächtigkeit eines runtime builders, trotzdem werden fehler schon zur compilezeit gefangen
        - con: state ist im typ encodiert, macht es schwer bis unmöglich (type erasure stunts), z.b. in einer if-bedingung konditional ein feld zu setzen
- da für jeden einsatzzweck ein anderes pattern optimal sein kann, habe ich mehrere für meine struct(s) implementiert

6.4.4 OpenFlags

6.5 Error handling

Kapitel 7

Evaluation

[7]

7.1 Beispiel-FS `hello2`

Kapitel 8

Conclusion

Kapitel 9

Future work

Bibliography

[1] W. Bugden and A. Alahmar, "Rust: The Programming Language for Safety and Performance." [Online]. Available: https://arxiv.org/abs/2206.05503

[2] R. Jung, J.-H. Jourdan, R. Krebbers, and D. Dreyer, "Safe systems programming in Rust: The promise and the challenge," *Communications of the ACM*, vol. 64, no. 4, pp. 144–152, 2020.

[3] A. Balasubramanian, M. S. Baranowski, A. Burtsev, A. Panda, Z. Rakamarić, and L. Ryzhyk, "System Programming in Rust: Beyond Safety," in *Proceedings of the 16th Workshop on Hot Topics in Operating Systems*, in HotOS '17. Whistler, BC, Canada: Association for Computing Machinery, 2017, pp. 156–161. doi: 10.1145/3102980.3103006.

[4] V. Astrauskas, P. Müller, F. Poli, and A. J. Summers, "Leveraging rust types for modular specification and verification," *Proc. ACM Program. Lang.*, vol. 3, no. OOPSLA, Oct. 2019, doi: 10.1145/3360573.

[5] V. Astrauskas, C. Matheja, F. Poli, P. Müller, and A. J. Summers, "How do programmers use unsafe rust?," *Proc. ACM Program. Lang.*, vol. 4, no. OOPSLA, Nov. 2020, doi: 10.1145/3428204.

[6] L. Seidel and J. Beier, "Bringing Rust to Safety-Critical Systems in Space," in *2024 Security for Space Systems (3S)*, 2024, pp. 1–8. doi: 10.23919/3S60530.2024.10592287.

[7] The MITRE Corporation, "2025 CWE Top 25 Most Dangerous Software Weaknesses." Accessed: Feb. 13, 2026. [Online]. Available: https://cwe.mitre.org/top25/archive/2025/2025_cwe_top25.html

Kapitel 10

Glossary

***UB* – Undefined Behaviour**: TODO 5, 13

***libfuse* – TODO libfuse**: TODO 13, 13, 13, 13, 13

***libfuse_wrapper* – the libfuse wrapper**: TODO - our lil' project 13, 13

***newtype_struct* – newtype struct**: TODO 14

***trampoline_function* – trampoline function**: TODO 13