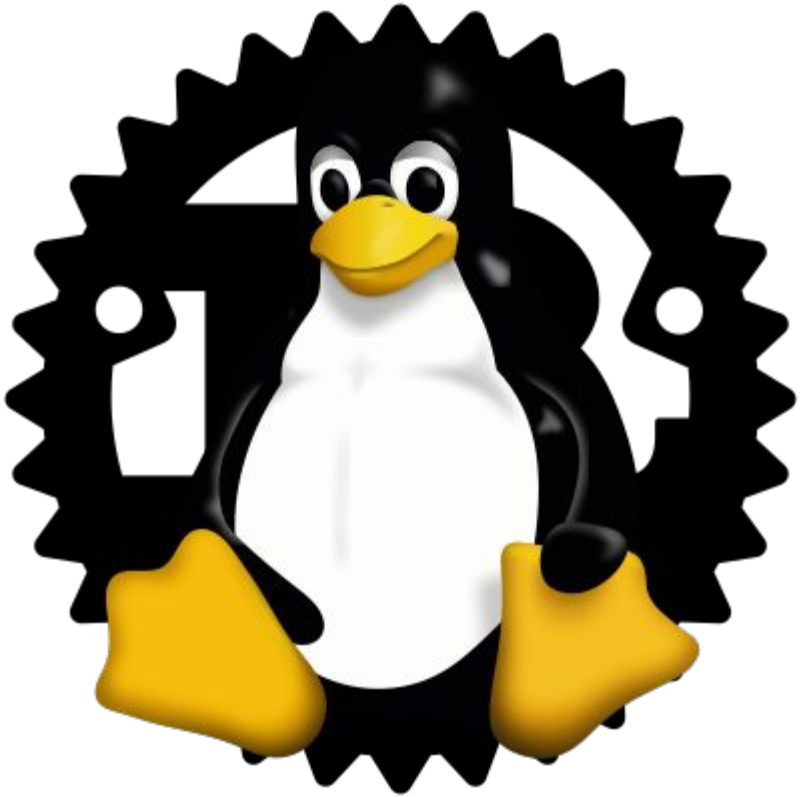
LF *live*

MENTORSHIP SERIES



Rust for Linux: Code Documentation & Tests

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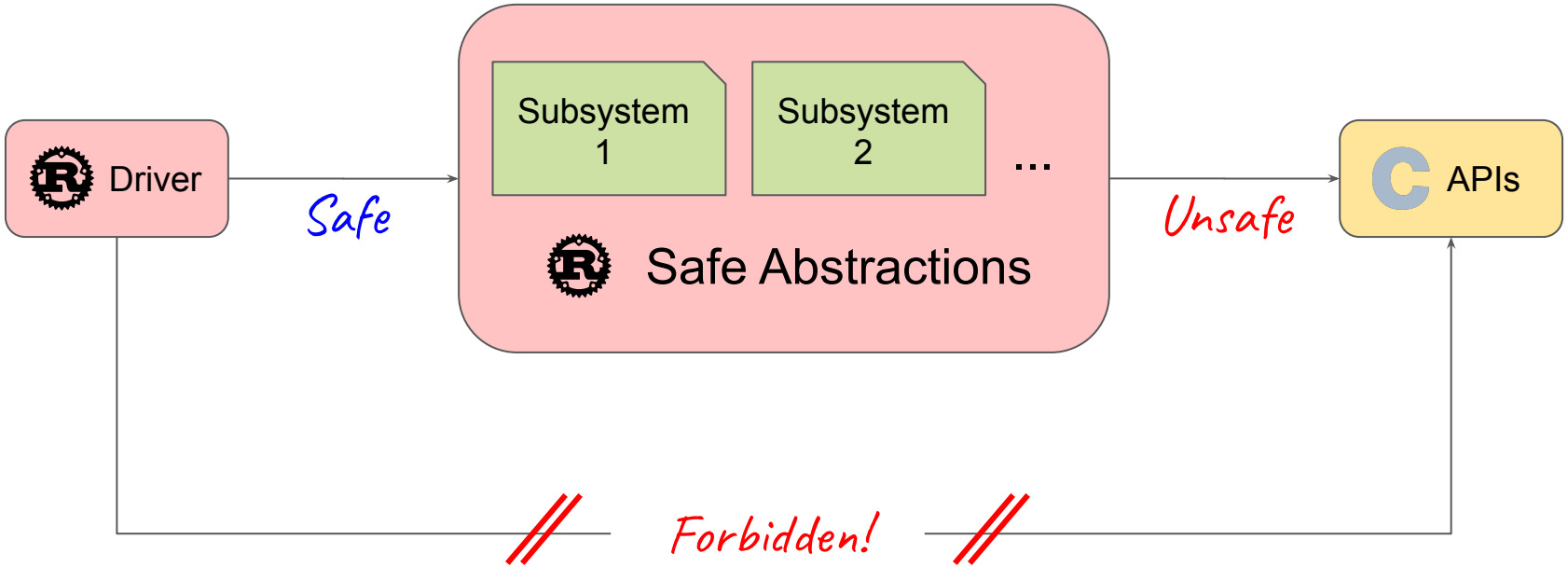
Recap

Rust in the kernel



Safe and Unsafe (functions)

Safe function: a function that does not trigger undefined behavior in any context and/or for any possible inputs.

That is, it does not have any precondition (regarding undefined behavior).

In other words, whatever a caller does, it does not produce undefined behavior.

Unsafe function: a function that is not safe, prefixed with the `unsafe` keyword.

This means it has safety preconditions.

Callers have to declare they are upholding the contract.

Safe and Unsafe (code)

Unsafe code: code inside an unsafe block.

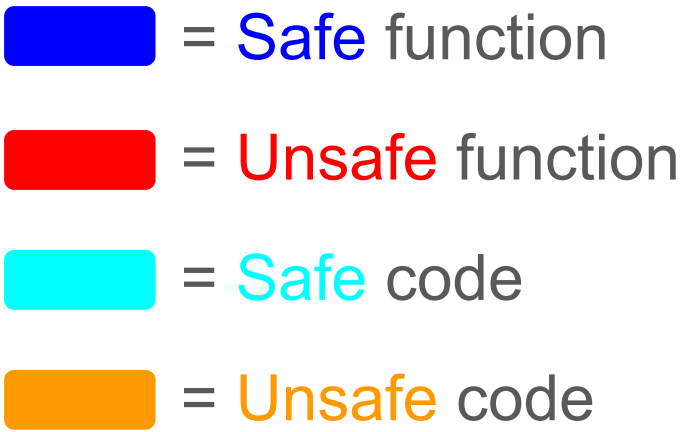
It has access to all operations.

Safe code: code that is outside an unsafe block (i.e. the default).

It cannot perform some operations (e.g. calling unsafe functions or dereferencing raw pointers).

Unsafe block: a block of code prefixed with the `unsafe` keyword.

Convention



The `deny(unsafe_op_in_unsafe_fn)` “dialect”

Kernel code is written in this “dialect”:

```
pub unsafe fn f() {
    g();            // The default in Rust: unsafe function implies unsafe block.
}

pub unsafe fn f() {
    unsafe { g(); } // Dialect: an explicit unsafe block is needed.
}
```

This may become the default in a future Rust edition.

Documenting a Rust function

Documenting a Rust function

Let us migrate this C function to Rust and document it:

```
i32 load(const i32 * p) {
    return *p;
}
```

Documenting a Rust function

In Rust, one may start writing:

```
pub fn load(p: *const i32) -> i32 {
    *p
}
```

Documenting a Rust function

We require that all public “items” (functions, types, modules...) must be documented.

```
/// Loads a 32-bit signed integer.
pub fn load(p: *const i32) -> i32 {
    *p
}
```

Documenting a Rust function

This code does not compile:

```
/// Loads a 32-bit signed integer.
pub fn load(p: *const i32) -> i32 {
    *p
}
```

```
error[E0133]: dereference of raw pointer is unsafe
              and requires unsafe block
 --> <source>:2:4
  |
2 |    *p
  |    ^^ dereference of raw pointer
  |
  = note: raw pointers may be null, dangling or unaligned;
    they can violate aliasing rules and cause data races:
    all of these are undefined behavior
```

Documenting a Rust function

A raw pointer dereference may introduce undefined behavior.

Rust requires an unsafe block.

```
/// Loads a 32-bit signed integer.
pub fn load(p: *const i32) -> i32 {
    unsafe { *p }
}
```

Documenting a Rust function

We require to justify why there is no undefined behavior.

For this, we use a `// SAFETY:` comment.

```rust
/// Loads a 32-bit signed integer.
pub fn load(p: *const i32) -> i32 {
    // SAFETY: ...
    unsafe { *p }
}
```

Documenting a Rust function

One way to justify it is to ask the callers to uphold a precondition.

```
/// Loads a 32-bit signed integer.
///
/// `p` must be valid, aligned and point to initialized memory.
pub fn load(p: *const i32) -> i32 {
    // SAFETY: ...
    unsafe { *p }
}
```

Documenting a Rust function

Now we have a precondition that is required to preserve safety.

Functions with safety preconditions are unsafe and must be marked as such.

```
/// Loads a 32-bit signed integer.
///
/// `p` must be valid, aligned and point to initialized memory.
pub unsafe fn load(p: *const i32) -> i32 {
    // SAFETY: ...
    unsafe { *p }
}
```

Documenting a Rust function

We require safety preconditions to be written in a `# Safety` section.

```
/// Loads a 32-bit signed integer.
///
/// # Safety
///
/// `p` must be valid, aligned and point to initialized memory.
pub unsafe fn load(p: *const i32) -> i32 {
    // SAFETY: ...
    unsafe { *p }
}
```

Documenting a Rust function

Now we can use the safety precondition to justify the unsafe block.

```
/// Loads a 32-bit signed integer.
///
/// # Safety
///
/// `p` must be valid, aligned and point to initialized memory.
pub unsafe fn load(p: *const i32) -> i32 {
    // SAFETY: The safety requirements of the function ensure we can
    // dereference and produce a valid value.
    unsafe { *p }
}
```

The `/// # Safety` section

Unsafe functions have safety preconditions that the caller must uphold.

The `# Safety` section in the documentation of an unsafe function describes those safety preconditions (requirements).

For instance, a function that takes a raw pointer and requires it to be valid must state so in this section. Callers must comply with it.

They should not be confused with the `// SAFETY:` comments.

It is also used in unsafe traits to describe requirements for implementers.

The `// SAFETY:` comments

A `// SAFETY:` comment must precede every unsafe block.

The comment must explain why the unsafe block does not invoke undefined behavior.

For instance, there must be a `// SAFETY:` comment above a raw pointer dereference justifying why the raw pointer is valid and aligned.

Other ways of justifying an unsafe block

For instance, consider:

```
/// Returns a string representing the error, if one exists.
pub fn name(&self) -> Option<&'static CStr> {
    // SAFETY: Just an FFI call, there are no extra safety requirements.
    let ptr = unsafe { bindings::errname(-self.0) };
    if ptr.is_null() {
        None
    } else {
        // SAFETY: The string returned by `errname` is static and `NUL`-terminated.
        Some(unsafe { CStr::from_char_ptr(ptr) })
    }
}
```

Type invariants

Type invariants

Assume there exists a `print_error()` C function.

Let us consider how to justify the following unsafe block:

```
pub fn print_error(code: i32) {
    // SAFETY: ...
    unsafe { bindings::print_error(code) }
}
```

Type invariants

First, we create a new type:

```
/// Represents an error code.
pub struct ErrorCode(i32);
```

Type invariants

First, we create a new type:

```
/// Represents an error code.
pub struct ErrorCode(i32);

impl ErrorCode {
    // Methods go here.
}
```

Type invariants

Then, we add a constructor:

```
/// Represents an error code.
pub struct ErrorCode(i32);

impl ErrorCode {
   /// Creates an [`ErrorCode`] from an error code.
   pub fn from_code(code: i32) -> Result<Self, ()> {
       if code > MAX_ERROR_CODE {
           return Err(());
       }

       Ok(Self(code))
   }
}
```

Type invariants

If an `ErrorCode` exists, then the code has to be valid by construction.

```
/// Represents an error code.
pub struct ErrorCode(i32);

impl ErrorCode {
    /// Creates an [`ErrorCode`] from an error code.
    pub fn from_code(code: i32) -> Result<Self, ()> {
        if code > MAX_ERROR_CODE {
            return Err(());
        }

        Ok(Self(code))
    }
}
```

Type invariants

We add a method to get back the raw error code:

```
/// Represents an error code.
pub struct ErrorCode(i32);

impl ErrorCode {
    // ...

    /// Returns the contained error code.
    pub fn to_code(&self) -> i32 {
        self.0
    }
}
```

Type invariants

We add a method to get back the raw error code:

```
/// Represents an error code.
pub struct ErrorCode(i32);

impl ErrorCode {
    // ...

    /// Returns the contained error code.
    ///
    /// The result is guaranteed to be a valid error code.
    pub fn to_code(&self) -> i32 {
        self.0
    }
}
```

Type invariants

Now we can modify our original function to take an `ErrorCode` instead:

```
pub fn print_error(code: i32) {
    // SAFETY: ...
    unsafe { bindings::print_error(code) }
}
```

```
pub fn print_error(ec: ErrorCode) {
    // SAFETY: ...
    unsafe { bindings::print_error(ec.to_code()) }
}
```

Type invariants

And write the justification for the unsafe block.

```rust
pub fn print_error(code: i32) {
    // SAFETY: ...
    unsafe { bindings::print_error(code) }
}
```

```rust
pub fn print_error(ec: ErrorCode) {
    // SAFETY: The error code returned by `to_code()` is always valid.
    unsafe { bindings::print_error(ec.to_code()) }
}
```

Type invariants

We say the `ErrorCode` type maintains an invariant.

We document type invariants in an `# Invariants` section:

```
/// Represents a valid error code.
pub struct ErrorCode(i32);
```

Type invariants

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We document type invariants in an `# Invariants` section:

```
/// Represents a valid error code.
///
/// # Invariants
///
/// The error code is within the interval of valid error codes, as defined
/// by specification X.
pub struct ErrorCode(i32);
```

Type invariants

We also document why invariants are upheld when we create or mutate the state:

```
impl ErrorCode {
    /// Creates an [`ErrorCode`] from an error code.
    pub fn from_code(code: i32) -> Result<Self, ()> {
        if code > MAX_ERROR_CODE {
            return Err(());
        }

        Ok(Self(code))
    }
}
```

Type invariants

We also document why invariants are upheld when we create or mutate the state:

```
impl ErrorCode {
    /// Creates an [`ErrorCode`] from an error code.
    pub fn from_code(code: i32) -> Result<Self, ()> {
        if code > MAX_ERROR_CODE {
            return Err(());
        }

        // INVARIANT: The check above ensures the type invariant holds.
        Ok(Self(code))
    }
}
```

The `/// # Invariants` section

Types may have invariants, i.e. properties all objects of that type satisfy.

The `# Invariants` section in the documentation of a type describes those invariants.

For instance, a type that wraps a pointer in a way that it kept always valid should document it in this section. Other code can rely on that.

They should not be confused with the `// INVARIANT:` comments.

The `// INVARIANT:` comments

An `// INVARIANT:` comment should be used when object state related to the invariant is mutated (including construction).

The comment explains why the type invariant is still preserved.

For instance, when a type with an invariant is constructed, an `// INVARIANT:` comment should precede the statement, explaining why the invariant holds.

It may be used for loop invariants as well.

An example from the kernel

```rust
/// An owned string that is guaranteed to have exactly one `NUL` byte, which is at the end.
///
/// Used for interoperability with kernel APIs that take C strings.
///
/// # Invariants
///
/// The string is always `NUL`-terminated and contains no other `NUL` bytes.
pub struct CString {
    buf: Vec<u8>,
}

impl CString {
    /// Creates an instance of [`CString`] from the given formatted arguments.
    pub fn try_from_fmt(args: fmt::Arguments<'_>) -> Result<Self, Error> {
        // ...

        // INVARIANT: We wrote the `NUL` terminator and checked above that no
        // other `NUL` bytes exist in the buffer.
        Ok(Self { buf })
    }
}
```

An example from the kernel

```
impl Deref for CString {
    type Target = CStr;

    fn deref(&self) -> &Self::Target {
        // SAFETY: The type invariants guarantee that the string is
        // `NUL`-terminated and that no other `NUL` bytes exist.
        unsafe { CStr::from_bytes_with_nul_unchecked(self.buf.as_slice()) }
    }
}
```

Writing examples

Writing examples

For instance, consider a data structure:

```
/// A red-black tree with owned nodes.
///
/// It is backed by the kernel C red-black trees.
///
/// # Invariants
///
/// Non-null parent/children pointers stored in instances of the `rb_node`
/// C struct are always valid, and pointing to a field of our internal
/// representation of a node.
pub struct RBTree<K, V> {
    // ...
}
```

Writing examples

We want to show how to use the data structure. For that, we add an `# Examples` section:

```
/// ...
///
/// # Examples
///
/// In the example below we do several operations on a tree.
/// We note that insertions may fail if the system is out of memory.
///
/// ```
/// # use kernel::prelude::*;
/// use kernel::rbtree::RBTree;
///
/// fn rbtest() -> Result {
///     // Create a new tree.
///     let mut tree = RBTree::new();
///
///     // Insert three elements.
///     tree.try_insert(20, 200)?;
///     tree.try_insert(10, 100)?;
///     tree.try_insert(30, 300)?;
///
/// ...
```

Writing examples

We can write assertions:

```
/// ...
///
///     // Check the nodes we just inserted.
///     {
///         let mut iter = tree.iter();
///         assert_eq!(iter.next().unwrap(), (&10, &100));
///         assert_eq!(iter.next().unwrap(), (&20, &200));
///         assert_eq!(iter.next().unwrap(), (&30, &300));
///         assert!(iter.next().is_none());
///     }
///
/// ...
```

Writing examples

We can write several independent examples:

```
/// # Examples
///
/// In the example below we do several operations on a tree. We note that insertions may fail if
/// the system is out of memory.
///
/// ```
///    First example...
/// ```
///
/// In the example below, we first allocate a node, acquire a spinlock, then insert the node into
/// the tree. This is useful when the insertion context does not allow sleeping, for example, when
/// holding a spinlock.
///
/// ```
///    Second example...
/// ```
///
/// In the example below, we reuse an existing node allocation from an element we removed.
///
/// ```
///    Third example...
/// ```
```

The `/// # Examples` section

Function, type, trait, module and crate documentation should contain an `# Examples` section with examples as needed to showcase and clarify their usage.

For instance, a module should provide examples showing the most common use cases of its APIs.

It is also useful to show common pitfalls.

Examples double as tests: they are compiled and run (when enabled).

How it looks like

Function core::ptr::read

1.0.0 (const: unstable) · source · [-]

```
pub unsafe fn read<T>(src: *const T) -> T
```

[–] Reads the value from `src` without moving it. This leaves the memory in `src` unchanged.

Safety

Behavior is undefined if any of the following conditions are violated:

- `src` must be valid for reads.
- `src` must be properly aligned. Use `read_unaligned` if this is not the case.
- `src` must point to a properly initialized value of type `T`.

Note that even if `T` has size `0`, the pointer must be non-null and properly aligned.

Examples

Basic usage:

```
let x = 12;
let y = &x as *const i32;

unsafe {
    assert_eq!(std::ptr::read(y), 12);
}
```

Manually implement `mem::swap`:

Function core::ptr::read

1.0.0 (const: unstable) · source · [-]

```
pub unsafe fn read<T>(src: *const T) -> T
```

[-] Reads the value from `src` without moving it. This leaves the memory in `src` unchanged.

`# Safety` section.

Safety

Behavior is undefined if any of the following conditions are violated:

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`# Examples` section.

Examples

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Examples

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let x = 12;
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unsafe {
    assert_eq!(std::ptr::read(y), 12);
}
```

Manually implement `mem::swap`:

Intra-doc links, automatically generated.

Function core::ptr::read

1.0.0 (const: unstable) · source · [-]

```
pub unsafe fn read<T>(src: *const T) -> T
```

[–] Reads the value from `src` without moving it. This leaves the memory in `src` unchanged.

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Behavior is undefined if any of the following conditions are violated:

Rust source code view.

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- `src` must be properly aligned. Use `read_unaligned` if this is not the case.
- `src` must point to a properly initialized value of type `T`.

Note that even if `T` has size `0`, the pointer must be non-null and properly aligned.

Examples

Basic usage:

```
let x = 12;
let y = &x as *const i32;

unsafe {
    assert_eq!(std::ptr::read(y), 12);
}
```

Manually implement `mem::swap`:

In core::ptr

Macros

addr_of
addr_of_mut

Structs

DynMetadata
NonNull

Traits

Pointee

Functions

copy
copy_nonoverlapping
drop_in_place
eq
from_raw_parts
from_raw_parts_mut
hash
metadata
null
null_mut

Click or press 'S' to search, '?' for more options...

Function core::ptr::read

1.0.0 (const: unstable) · source · [-]

```
pub unsafe fn read<T>(src: *const T) -> T
```

[–] Reads the value from `src` without moving it. This leaves the memory in `src` unchanged.

Client-side search.

Safety

Behavior is undefined if any of the following conditions are violated:

- `src` must be valid for reads.
- `src` must be properly aligned. Use `read_unaligned` if this is not the case.
- `src` must point to a properly initialized value of type `T`.

Note that even if `T` has size `0`, the pointer must be non-null and properly aligned.

Examples

Basic usage:

```
let x = 12;
let y = &x as *const i32;

unsafe {
    assert_eq!(std::ptr::read(y), 12);
}
```

Manually implement `mem::swap`:

Struct kernel::rbtree::RBTree [-][src]

```
pub struct RBTree<K, V> { /* fields omitted */ }
```

[–] A red-black tree with owned nodes.

It is backed by the kernel C red-black trees.

Invariants

Non-null parent/children pointers stored in instances of the `rb_node` C struct are always valid, and pointing to a field of our internal representation of a node.

Examples

In the example below we do several operations on a tree. We note that insertions may fail if the system is out of memory.

```
use kernel::rbtree::RBTree;

fn rbtest() -> Result {
    // Create a new tree.
    let mut tree = RBTree::new();

    // Insert three elements.
    tree.try_insert(20, 200)?;
    tree.try_insert(10, 100)?;
    tree.try_insert(30, 300)?;

    // Check the nodes we just inserted.
    {
        let mut iter = tree.iter();
        assert_eq!(iter.next().unwrap(), (&10, &100));
```

Other notes

Documenting modules

If a module is written in its own file, then we document it inside it using `//!`:

```
// SPDX-License-Identifier: GPL-2.0

//! Red-black trees.
//!
//! C header: [`include/linux/rbtree.h`](../../../../include/linux/rbtree.h)
//!
//! Reference: <https://www.kernel.org/doc/html/latest/core-api/rbtree.html>

use crate::{bindings, Result};
use alloc::boxed::Box;
// ...
```

Other sections

In the standard Rust library, which we use, other fairly common sections are:

- `# Errors` section.
- `# Panics` section.

We may start using these, or new ones, too, as we explore how to best document consistently the code.

Writing prose

Feel free to document any item extensively, including writing prose divided with extra sections that are not the “standard” ones.

Typically, this applies to modules and types.

For instance, a good example is the documentation for `Vec` from the standard library.

These docs may be enough to replace the usual `Documentation/` ones.

```
stack.push(3);

while let Some(top) = stack.pop() {
    // Prints 3, 2, 1
    println!("{}", top);
}
```

Indexing

The `Vec` type allows to access values by index, because it implements the `Index` trait. An example will be more explicit:

```
let v = vec![0, 2, 4, 6];
println!("{}", v[1]); // it will display '2'
```

However be careful: if you try to access an index which isn't in the `Vec`, your software will panic! You cannot do this:

```
let v = vec![0, 2, 4, 6];
println!("{}", v[6]); // it will panic!
```

Use `get` and `get_mut` if you want to check whether the index is in the `Vec`.

Slicing

A `Vec` can be mutable. On the other hand, slices are read-only objects. To get a slice, use `&`. Example:

```
fn read_slice(slice: &[usize]) {
    // ...
}

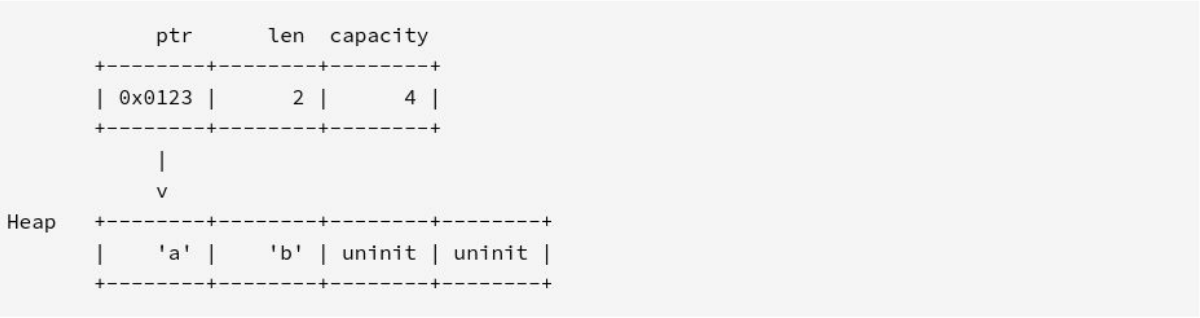
let v = vec![0, 1];
read_slice(&v);

// ... and that's all!
// you can also do it like this:
```

details are very subtle — if you intend to allocate memory using a `Vec` and use it for something else (either to pass to unsafe code, or to build your own memory-backed collection), be sure to deallocate this memory by using `from_raw_parts` to recover the `Vec` and then dropping it.

If a `Vec` *has* allocated memory, then the memory it points to is on the heap (as defined by the allocator Rust is configured to use by default), and its pointer points to `len` initialized, contiguous elements in order (what you would see if you coerced it to a slice), followed by `capacity - len` logically uninitialized, contiguous elements.

A vector containing the elements `'a'` and `'b'` with capacity 4 can be visualized as below. The top part is the `Vec` struct, it contains a pointer to the head of the allocation in the heap, length and capacity. The bottom part is the allocation on the heap, a contiguous memory block.



- **uninit** represents memory that is not initialized, see `MaybeUninit`.
- Note: the ABI is not stable and `Vec` makes no guarantees about its memory layout (including the order of fields).

`Vec` will never perform a "small optimization" where elements are actually stored on the stack for two reasons:

- It would make it more difficult for unsafe code to correctly manipulate a `Vec`. The contents of a `Vec` wouldn't have a stable address if it were only moved, and it would be more difficult to determine if a `Vec` had actually allocated memory.
- It would penalize the general case, incurring an additional branch on every access.

`Vec` will never automatically shrink itself, even if completely empty. This ensures no unnecessary allocations or deallocations occur. Emptying a `Vec` and then filling it back up to the same `len` should incur no calls to the allocator. If you wish to free up unused memory, use `shrink_to_fit` or `shrink_to`.

Other coding guidelines

No direct access to C bindings.

Rust 2021 edition & idioms.

No undocumented public APIs.

No unneeded panics.

No infallible allocations.

Clippy linting enabled.

Automatic formatting enforced.

...

Useful references

`rustdoc` guide on writing documentation:

https://doc.rust-lang.org/rustdoc/how-to-write-documentation.html

`rustdoc` guide on writing documentation tests:

https://doc.rust-lang.org/rustdoc/documentation-tests.html

Rust for Linux coding guidelines:

https://github.com/Rust-for-Linux/linux/blob/rust/Documentation/rust/coding-guidelines.rst

Tests

Kinds of tests

In Rust projects, there are usually 3 kinds of tests:

- Unit tests (`#[test]` in the source code).
- Documentation tests (e.g. `# Examples` section).
- Integration tests (in a `tests/` folder).

We would like to adapt those for the kernel:

- We are working on integrating these with KUnit.

Unit tests

```
#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn test_cstr_to_str() {
        let good_bytes = b"\xf0\x9f\xa6\x80\0";
        let checked_cstr = CStr::from_bytes_with_nul(good_bytes).unwrap();
        let checked_str = checked_cstr.to_str().unwrap();
        assert_eq!(checked_str, "🦀");
    }

    #[test]
    #[should_panic]
    fn test_cstr_to_str_panic() {
        let bad_bytes = b"\xc3\x28\0";
        let checked_cstr = CStr::from_bytes_with_nul(bad_bytes).unwrap();
        checked_cstr.to_str().unwrap();
    }
}
```

CI

The tests are compiled and run in the Rust for Linux CI before merging new code.

Currently, this only tests a few configurations.

Build testing with other configurations was recently added to the 0-DAY CI Kernel Test Service.

Conclusions

Conclusions

Rust requires unsafe blocks around potentially-UB operations.

It also provides a way to mark functions that may trigger UB.

On top of that, in Rust for Linux:

- Unsafe functions do not imply an unsafe block (`unsafe_op_in_unsafe_fn`).
- Unsafe blocks must be justified (`// SAFETY`).
- Unsafe functions must be marked as such (`unsafe`).
- Safety preconditions must be documented (`# Safety`).

Conclusions

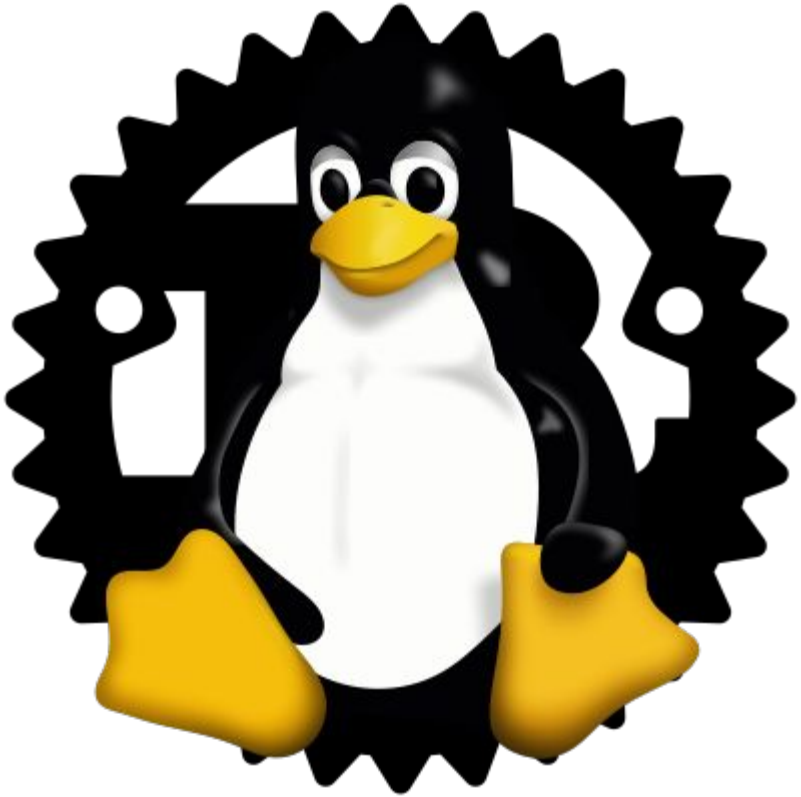
Type invariants are a key tool to develop APIs with less safety preconditions.

Code documentation does not change the behavior of the code, but:

- They make reviewing the soundness of a module easier.
- The `# Safety` sections are critical for users to understand the preconditions.

Writing examples is useful to document, test and make sure the documentation stays aligned with the code.

We are working on integrating the testing support with the kernel.



Rust for Linux: Code Documentation & Tests

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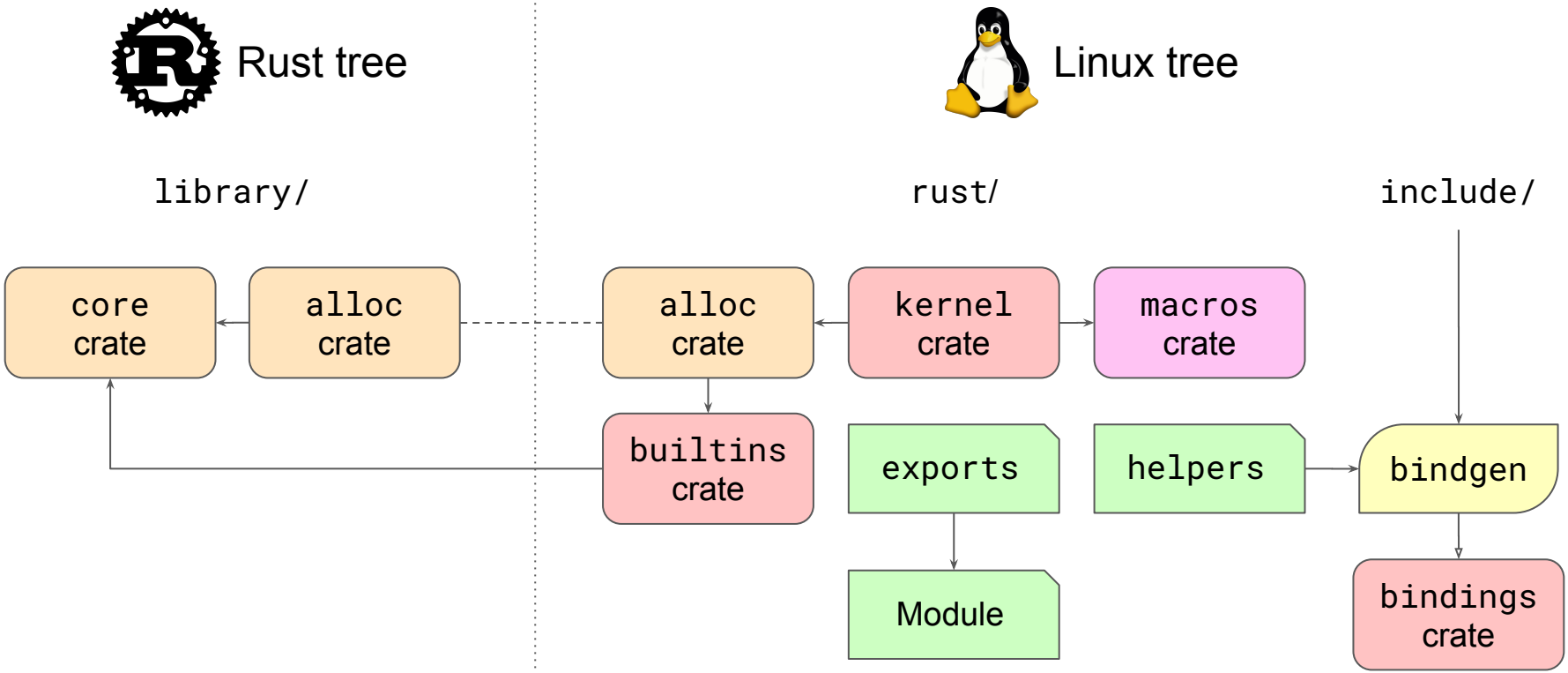
LF live MENTORSHIP SERIES

Thank you for joining us today!

We hope it will be helpful in your journey to learning more about effective and productive participation in open source projects. We will leave you with a few additional resources for your continued learning:

- The LF Mentoring Program is designed to help new developers with necessary skills and resources to experiment, learn and contribute effectively to open source communities.
- Outreachy remote internships program supports diversity in open source and free software
- Linux Foundation Training offers a wide range of free courses, webinars, tutorials and publications to help you explore the open source technology landscape.
- Linux Foundation Events also provide educational content across a range of skill levels and topics, as well as the chance to meet others in the community, to collaborate, exchange ideas, expand job opportunities and more. You can find all events at events.linuxfoundation.org.

Backup slides


Rust tree
Linux tree
library/
rust/
include/
core crate
alloc crate
alloc crate
kernel crate
macros crate
builtins crate
exports
helpers
bindgen
Module
bindings crate

(Un)safe functions vs. (un)safe code

Safe function with only safe code	Unsafe function with only safe code
Safe function with unsafe code	Unsafe function with unsafe code

What happens if we make a mistake?

If a safe function is not actually safe, then it is called **unsound**.

This is considered a bug.

In the standard library, a CVE is assigned.

```
fn f(p: *const i32) -> i32 {
    unsafe { *p }
}
```