Lecture 10

Unsafe Rust

Rust's promise to you

If you satisfy the Rust compiler, your program will never exhibit undefined behavior

- Use after free
- Buffer overflow
- Data race
- Invalid reference

🚨Really bad🚨

Rust programs are still free to encounter bad (but safe!) behavior

- Deadlock
- Leak memory
- Overflow integers
- Abort the program
- Accidentally delete the database
- Panics

Bad, but manageable

Sometimes, safety is too restrictive

Example:

- Python is safe, but at the cost of terrible performance. For performance critical code, write it in C and call from python
  - ```
    import numpy as np
    np.matmul(A,B)
    ```
- Java is safe, but base collections like arrays can't be implemented in the language. They're special-cased by the compiler

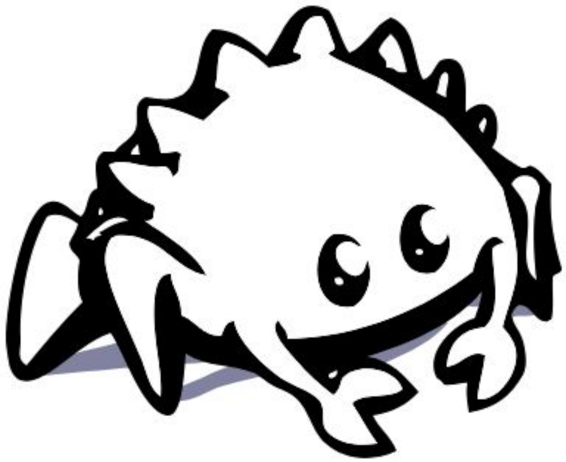
The ergonomics/safety of calling between languages is terrible

- type mismatches
- translating data representation
- etc.

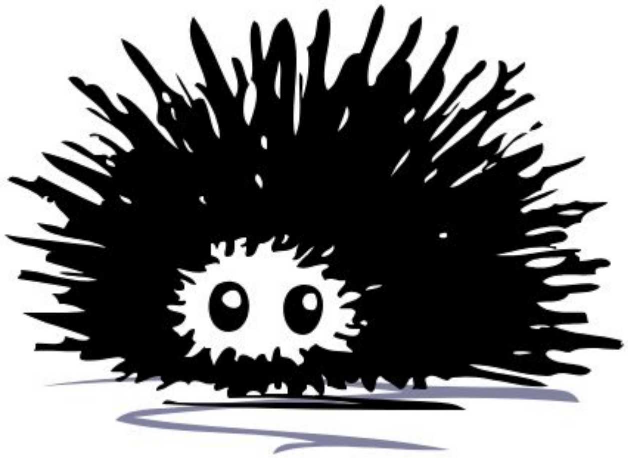
> 💡 What if we could write safe and unsafe code in the same language?
    ```

Rust contains two languages

Safe Rust



Unsafe Rust



Rust contains two languages

Safe Rust

- Everything we've done up to this point
- If it compiles, it's safe
- You should spend as much time as possible writing safe Rust

Unsafe Rust

- Safe Rust, plus additional powers
- Safe Rust's guarantees don't apply: segfaults and data races could occur

How to do this?
Use *unsafe* Rust to build safe abstractions that you can call from *safe* Rust

- Mutex
- RefCell
- Vec

How to build safe abstractions on unsafe?

Two components

- Check to make sure the unsafe is valid
- Perform the unsafe

E.x. index into slice represented with raw pointer

- Impossible to do in safe Rust; compiler can't verify size of allocation

```
fn get(slice: &mut [T], index: usize)
  -> Option<&mut T> {
   if self < slice.len() {
       // SAFETY: `index` is checked to be in bounds.
       unsafe { Some((slice.ptr + index).read()) }
   } else {
       None
   }
}
```

How to build safe abstractions on unsafe?

Two components

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       None
   }
}
```

Aside: `unsafe` is poorly named

Unsafe blocks are not for causing undefined behavior

- Dereferencing null pointers is a bad idea regardless

Unsafe blocks are for doing things that the compiler can’t verify are safe.

- Better names:
  - `unchecked` blocks
  - `trust_me_this_is_right` blocks

Why should you care about unsafe?

If the goal is to write unsafe Rust as little as possible why should you care?

- You don't have to! You can write lots of functional, performant Rust code without ever touching unsafe

However, if you want to implement a fast data structure that others depend on, it's worthwhile to put in extra effort to implement optimizations that require unsafe

- Vec
- Mutex
- Hashmap

Unsafe super powers

In unsafe Rust you can...

- Dereference raw pointers
- Access mutable global variables

That's it! Importantly...

- Ownership still applies
- Reference rules still apply (mutability, validity)

Let's look at examples of using these powers

Dereference raw pointers

References are like pointers, but more restrictive

- Can't dangle (point to invalid memory)
- Can't have multiple mutable references

What if we just want plain old pointers?

```
let address: usize = 0x00012345;
let ptr: *const i32 = address as *const i32;
unsafe {
  println!("Value at address: {}", *ptr);
}
```

```
let address: usize = 0x00000000;
let ptr: *mut i32 = address as *mut i32;
unsafe {
    *ptr = 42;
}
```

Dereference raw pointers

References are like pointers, but more restrictive

- Can't dangle (point to invalid memory)
- Can't have multiple mutable references

What if we just want plain old pointers?

Pointers...

- can point to invalid memory
- can be null
- are either mutable or const

```
let address: usize = 0x00012345;
let ptr: *const i32 = address as *const i32;
unsafe {
  println!("Value at address: {}", *ptr);
}
```

```
let address: usize = 0x00000000;
let ptr: *mut i32 = address as *mut i32;
unsafe {
    *ptr = 42;
}
```

Mutable globals

Mutating global variables is unsafe. Why?

```rust
static mut counter: u32 = 0;

fn main() {
    counter = counter + 1;
}
```

```
error[E0133]: use of mutable static is unsafe and
requires unsafe function or block
--> globals.rs:4:15
  |
4 |     counter = counter + 1;
  |               ^^^^^^^ use of mutable static
```

Mutable globals

Mutating global variables is unsafe. Why?

- data races

```rust
static mut counter: u32 = 0;

fn main() {
    counter = counter + 1;
}
```

```
error[E0133]: use of mutable static is unsafe and
requires unsafe function or block
--> globals.rs:4:15
  |
4 |     counter = counter + 1;
  |               ^^^^^^^ use of mutable static
 = note: mutable statics can be mutated by multiple
threads: aliasing violations or data races will cause
undefined behavior
```

Mutable globals

How to fix with unsafe?

By convention: provide a `SAFETY` comment that explains how you've manually verified that the code in the `unsafe` block is safe.

```rust
static mut counter: u32 = 0;

fn main() {
    // SAFETY: this application
    // is single-threaded
    unsafe {
        counter = counter + 1;
    }
}
```

```
free()
    The free() function frees the memory space pointed to by ptr, which must
    have  been returned by a previous call to malloc() or related functions.
    Otherwise, or if ptr has already been freed, undefined behavior  occurs.
    If ptr is NULL, no operation is performed.
```

Unsafe functions

Based on the signature, what do you think is the difference between these functions? Why would you call one or the other?

```
impl Vec<T> {
    pub fn get(&self, index: usize) -> Option<&T>
    pub unsafe fn get_unchecked(&self, index: usize) -> &T
}
```

Unsafe functions

Based on the signature, what do you think is the difference between these functions? Why would you call one or the other?

Out-of-bounds checks are required to maintain safety. `get_unchecked` skips the bounds check.

```
impl Vec<T> {
    pub fn get(&self, index: usize) -> Option<&T>
    pub unsafe fn get_unchecked(&self, index: usize) -> &T
}
```

Unsafe functions

Functions marked `unsafe` don't necessarily use unsafe internally.

`unsafe` on a function means: "calling this function correctly requires upholding properties that the compiler cannot check for you"

Unsafe functions come with a comment saying what properties you need to uphold

```
[-] pub unsafe fn get_unchecked<I>(
                    ...
```

Safety

Calling this method with an out-of-bounds index is *undefined behavior* even if the resulting reference is not used.

```
free()
    The free() function frees the memory space pointed to by ptr, which must
    have  been returned by a previous call to malloc() or related functions.
    Otherwise, or if ptr has already been freed, undefined behavior  occurs.
    If ptr is NULL, no operation is performed.
```

Unsafe functions

Is there an inefficiency here?

```rust
fn sum(v: &Vec<usize>) -> usize {
    let mut counter = 0;
    for i in 0..v.len() {
        counter += v[i];
    }
    counter
}
```

Unsafe functions

Is there an inefficiency here?

```
fn sum(v: &Vec<usize>) -> usize {
    let mut counter = 0;
    for i in 0..v.len() {
        counter += v[i];
    }
    counter
}
```

What's an even better way to write this?

```
fn sum_unsafe(v: &Vec<usize>) -> usize {
    let mut counter = 0;
    for i in 0..v.len() {
        unsafe {
            counter +=
v.get_unchecked(i);
        }
    }
    counter
}
```

Unsafe functions

```
fn sum_iter(v: &Vec<usize>) -> usize {
    let mut counter = 0;
    for n in v.iter() {
        counter += n;
    }
    counter
}
```

No bounds check, no unsafe ✅

Unsafe traits

Unsafe function -> need to uphold special properties to **call this function**

Unsafe trait -> need to uphold special properties to **implement this trait**

Only two examples in the standard library

```
pub unsafe trait Send { }
pub unsafe trait Sync { }
```

Improper implementation of Send/Sync will cause a data race, which is undefined behavior

Compiler can't check these!

Comparison: `PartialEq`

```
pub trait PartialEq<Rhs> {
    fn eq(&self, other: &Rhs) -> bool;
    fn ne(&self, other: &Rhs) -> bool { ... }
}
```

Implementations must ensure that `eq` and `ne` are consistent with each other:

- `a != b` if and only if `!(a == b)`.

But wait, other traits have additional properties that need to be upheld?

Comparison: PartialEq

```
pub trait PartialEq<Rhs> {
    fn eq(&self, other: &Rhs) -> bool;
    fn ne(&self, other: &Rhs) -> bool { ... }
}
```

Implementations must ensure that `eq` and `ne` are consistent with each other:

- `a != b` if and only if `!(a == b)`.

```
struct Id(u32)
impl std::cmp::PartialEq for Id {
    fn eq(&self, other: &Self) -> bool {
        self.0 == other.0
    }
    fn neq(&self, other: &Self) -> bool {
        self.0 == other.0
    }
}
```

Comparison: PartialEq

```
pub trait PartialEq<Rhs> {
    fn eq(&self, other: &Rhs) -> bool;
    fn ne(&self, other: &Rhs) -> bool { ... }
}
```

Implementations must ensure that eq and ne are consistent with each other:

- a != b if and only if !(a == b).

```
struct Id(u32)
impl std::cmp::PartialEq for Id {
    fn eq(&self, other: &Self) -> bool {
        self.0 == other.0
    }
    fn neq
        se
    }
}
```

```
// Requires PartialEq
let mut names = vec![Id(0), Id(1), Id(2)];
names.binary_search(&Id(1));
```

Because it's safe to implement PartialEq, binary_search can't rely on the eq and neq being implemented properly

Unsafe traits

Rust could have `UnsafePartialEq` that is unsafe to implement but allows code to rely on the fact that `eq`/`neq` are implemented correctly

Why would having `UnsafePartialEq` as the default equality trait be better or worse than the current default?

Unsafe traits

Rust could have `UnsafePartialEq` that is unsafe to implement but allows code to rely on the fact that `eq`/`neq` are implemented correctly

Why would having `UnsafePartialEq` as the default equality trait be better or worse than the current default?

Pro:

PartialEq is implemented more often than it's consumed

- Not marking the trait `unsafe` makes things easier for the implementer, but harder for the consumer

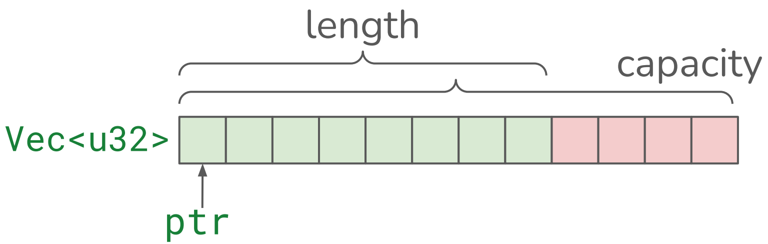
Con:

Functions like `binary_search` might be leaving performance on the table

Case Study: implementing Vec

`Vec` is implemented with unsafe code

For full tutorial, see [the Rustnomicon]




```
pub struct Vec<T> {
    ptr: *mut T,
    cap: usize,
    len: usize,
}

pub fn push(&mut self, elem: T) {
    if self.len == self.cap { self.grow(); }
    unsafe {
      ptr::write(self.ptr.add(self.len), elem);
    }
    self.len += 1;
}
```

How is this better than C?

The standard library has lots of unsafe code, so are Rust's guarantees all a lie and we should go back to using C?

No! Separating `unsafe` code greatly reduces the set of code that needs to be manually checked.

- When a segfault occurs, only need to check for bugs in your `unsafe` code

How safe and unsafe interact

Safe code has to trust unsafe code implicitly

- e.g. all safe code **can assume** that `Send` and `Sync` types are implemented properly

Unsafe code can't trust safe code at all

- Unsafe code in BTreeMap **can't assume** that `PartialEq` is implemented properly

Writing `unsafe` code is hard

- You must be defensive

Zooming out

Undefined behavior: what happens when code executes that violates certain rules, like reading from uninitialized memory

Safe Rust: if the program compiles, no undefined behavior will occur

`unsafe` block: allows writing code that compiles, but might cause undefined behavior.

`unsafe` function: function that could cause undefined behavior if you don't check the documentation to see what contracts you must uphold

`unsafe` trait: trait that could cause undefined behavior if you don't check the documentation to see what contracts your type must uphold

Unsafe is hard: panic safety

New trick: panics can be caught

Works similar to try/catch in other languages, but shouldn't be used that way

```
let result = panic::catch_unwind(|| {
   panic!("oh no!");
});
assert!(result.is_err());
```

Panic safety: if your code panics but the panic is caught, are data structures left in a valid state?

Unsafe is hard: panic safety

```
pub fn push(&mut self, elem: T) {
    self.len += 1;
    if self.len == self.cap { self.grow(); }
    unsafe {
      ptr::write(self.ptr.add(self.len), elem);
    }

}
```

Panic safety: if your code panics but the panic is caught, are data structures left in a valid state?

Is this code panic safe?

Unsafe is hard: panic safety

```
pub fn push(&mut self, elem: T) {
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Is this code panic safe?

No! If `grow()` panics, the length has been incremented but no new element has been added

Unsafe is hard: panic safety

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    }

}
```

Panic safety: if your code panics but the panic is caught, are data structures left in a valid state?

How would we implement `Vec` without unsafe? Do we need to worry about panic safety?

Is this code panic safe?

No! If `grow()` panics, the length has been incremented but no new element has been added

Unsafe is hard: pointer vs. reference

Raw pointers can *dangle*: point to invalid memory

Even in unsafe, references can't dangle

```
impl Vec<T> {
   pub unsafe fn get_unchecked(&self, index:
usize) -> &T
}

fn main() {
    let v: Vec<u32> = Vec::new();
    let first: *const u32 = unsafe {
        v.get_unchecked(0) as *const u32
    };
}
```

Is this code allowed?

Unsafe is hard: pointer vs. reference

Raw pointers can *dangle*: point to invalid memory

Even in unsafe, references can’t dangle

```
impl Vec<T> {
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usize) -> &T
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fn main() {
    let v: Vec<u32> = Vec::new();
    let first: *const u32 = unsafe {
        v.get_unchecked(0) as *const u32
    };
}
```
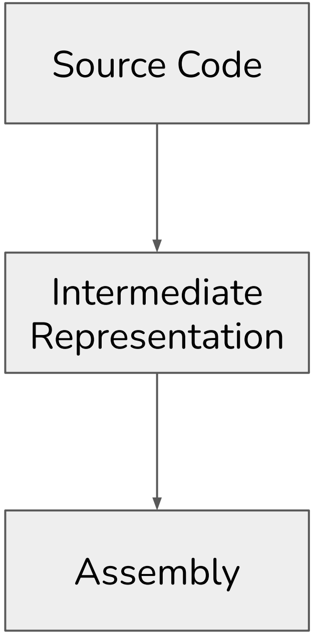

Is this code allowed?

No! `get_unchecked` produces a dangling reference, even if it’s immediately converted to a pointer

Bottom line: writing unsafe is hard, what can we do about it?

Normal Rust compilation



Very easy to analyze

- Type information
- Lifetimes

Hard to analyze, fast to run

- Just reasons about bytes
- No lifetimes or types

Idea:

When testing, instead of running assembly, run the intermediate representation and check for bugs

https://play.rust-lang.org/?version=stable&mode=debug&edition=2024&gist=b634f495eb0bc354ad6f50e858779e78

MIRI

A tool that detects undefined behavior while Rust code runs

Slow to run, so only run your code with MIRI during development

How MIRI works:

Run Rust code in a sandbox

- Track allocation sizes, lifetimes, etc.

If unsafe code causes undefined behavior, print an error.

Real bugs in standard library found with MIRI

- Debug for vec_deque::Iter accessing uninitialized memory
- Vec::into_iter doing an unaligned ZST read
- From<&[T]> for Rc creating a not sufficiently aligned reference

https://play.rust-lang.org/?version=stable&mode=debug&edition=2021&gist=b4ca5b55b0c881a3cad3488be9054387

Final Project Ideas

Graphical applications

- Chat app (project 3 as a starting point)
- Music player, Code editor, Video game

Challenging projects from other domains

- Ray tracer, garbage collector, compiler, database, load balancer, consensus algorithm, file system, scheduler

Misc.

- Write a smart contract in Rust on the Solana blockchain
- Run Rust in the browser using WebAssembly
- Run Rust on Arduino using no_std

Open source contributions

- Build a data structure using unsafe and publish it to crates.io
- Implement data science functions in Rust, then allow them to be called from Python and publish the library
- A blazing fast command line tool

Last year's projects

Command-line apps

- **Stock tracker, git client,**

Games

- **Rhythm game, tetris, multiplayer**

Graphical apps

- **file manager**

Previous Projects

Command-line apps

- stock tracker, git client

Games

- rhythm game, tetris, multiplayer game

Graphical apps

- file manager

Other

- load balancer
- scipy