LECTURE 27

Guest Lecture by Mark Mansi (CS 538)

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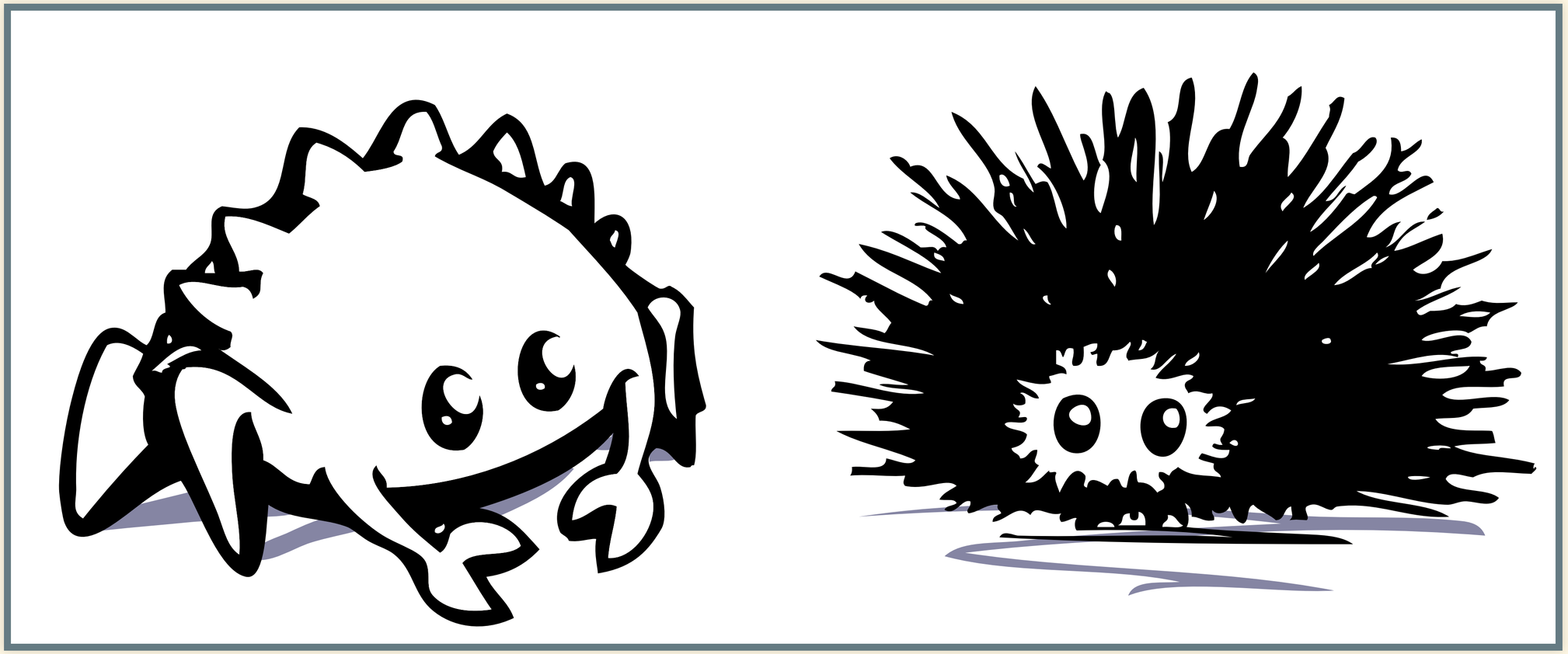

Safe and Unsafe Rust

AGENDA

FOUNDATIONS

- What does Rust actually guarantee?
- Introducing `unsafe`
- Unsafety and Invariants
- Using Abstraction

GETTING STARTED WITH *UNSAFE* RUST

- Raw pointers
- Links to further reading

WHAT DOES RUST

GUARANTEE?

GOAL: FEW BUGS, FASTER PROGRAMS

- Avoid doing non-sensical or wrong things…
- … and find out when we do.
- Enable compiler optimizations.

LANGUAGE SPEC

Defines allowed, disallowed, and unspecified behaviors.

- Examples of disallowed:
  - dereference `null` pointer
  - have a `bool` that is not `true` or `false`
  - access array out of bounds
- Examples of unspecified:
  - In C/C++: `a = f(b) + g(c)`
  - which is first: `f` or `g`?

UNDEFINED BEHAVIOR (UB)

there are no restrictions on the behavior of the program.

Compilers are not required to diagnose undefined behavior (although many simple situations are diagnosed),

and the compiled program is not required to do anything meaningful.

IMPLICATIONS OF UB

- Correct programs don’t invoke UB
- UB can be hard to debug
- Compilers can assume no UB when optimizing

EXAMPLE FROM C++

```
char *p = "I'm a string literal";
p[3] = 'x';
```

ISO C++ forbids mutating string literals (ISO C++ §2.13.4p2)

EXAMPLE FROM C++

```
char *p = nullptr;
p[3] = 'x'; // Program is allowed to eat laundry here
```

Deferencing an invalid pointer is forbidden (ISO C §6.5.3.2p4)

SAFETY IN RUST

"Safety" means no UB

- Memory safety
  - e.g. accesses are to valid values only
  - e.g. prohibiting mutable aliasing pointers
- Thread safety
  - e.g. mutable aliasing state
- Enforced by type system

NO UB IN SAFE RUST

```rust
let x = Vec::new(); // Empty Vec
println!("Out of bounds: {}", x[2]); // Panic, not UB!
```

```rust
fn foo() -> &usize {
    let x = 3;
    &x // Return reference to stack variable (allowed in C)

    // Doesn't compile (borrow checker error), not UB!
}
```

UB IN (UNSAFE) RUST

- Dereferencing null, dangling, or unaligned pointers
- Reading uninitialized memory
- Breaking the pointer aliasing rules
- Producing invalid primitive values:
  - dangling/null references
  - null `fn` pointers
  - a `bool` that isn't `true` or `false`

MORE UB IN (UNSAFE) RUST

- Producing invalid primitive values:
  - an undefined enum discriminant
  - a `char` outside the ranges `[0x0, 0xD7FF]` and `[0xE000, 0x10FFFF]`
  - A non-utf8 `str`
- Unwinding into another language
- Causing a data race

WHAT DOES RUST *NOT* GUARANTEE?

EXAMPLE

```rust
struct Foo(Option<Arc<Mutex<Foo>>>);

impl Drop for Foo {
    /// Implement a destructor for `Foo`
    fn drop(&mut self) {
        // <do some clean up>
    }
}
```

EXAMPLE (CONTINUED)

```rust
fn do_the_foo_thing() {
    let foo1 = Arc::new(Mutex::new(Foo(None)));
    let foo2 = Arc::new(Mutex::new(Foo(None)));

    // Reference cycle
    foo1.lock().unwrap().0 = Some(Arc::clone(&foo2));
    foo2.lock().unwrap().0 = Some(Arc::clone(&foo1));

    // `foo1` and `foo2` are never dropped!
    // Memory never freed. Foo::drop never called. No UB!
}
```

SAFE RUST CAN STILL...

- Panic (“graceful” crashing)
- Deadlock (two threads both waiting for each other)
- Leak of memory and other resources (never freed back to the system)
- Exit without calling destructors (never clean up)
- Integer overflow (`MAX_INT + 1`)

A DILEMMA

EXAMPLE

In my program (Rust):

```rust
/// Read from file `fd` into buffer `buf`.
fn read_file(fd: i32, buf: &mut [u8]) {
    let len = buf.len();
    libc::read(fd, buf.as_mut_ptr(), len);
}
```

In `libc` (C):

```c
ssize_t read(int fd, void *buf, size_t count) {
    // oops bug accidentally overflows `buf`
}
```

RESTORING SAFETY

Compiler error: no unsafe C from safe Rust!

```rust
/// Read from the file descriptor into the buffer.
fn read_file(fd: i32, buf: &mut [u8]) {
    let len = buf.len();
    libc::read(fd, buf.as_mut_ptr(), len); // Compile error!
}
```

Ok, but how do we call C libraries or the OS?

`unsafe`

- Sometimes need to do something potentially unsafe
  - system calls
  - calls to C/C++ libraries
  - interacting with hardware
  - writing assembly code
  - …

Compiler can't check these: Be careful!

EXAMPLE

```rust
/// Read from the file descriptor into the buffer.
fn read_file(fd: i32, buf: &mut [u8]) {
    let len = buf.len();
    unsafe {
        libc::read(fd, buf.as_mut_ptr(), len);
    }
}
```

Rust compiles, but C code may do something bad: Be careful!

WHAT DOES

`unsafe` MEAN?

"AUDIT `unsafe` BLOCKS"

From `libstd` `Vec`. Consider `set_len`:

```rust
pub struct Vec<T> {
    buf: RawVec<T>,
    len: usize,
}

impl Vec {
    /// Sets the length of the vector to `new_len`.
    pub fn set_len(&mut self, new_len: usize) {
        self.len = new_len;
    }
}
```

"AUDIT `unsafe` BLOCKS"

```rust
fn main() {
    let mut my_vec = Vec::with_capacity(0); // empty vector
    my_vec.set_len(100);

    my_vec[30] = 0; // UB!
}
```

Huh?!? UB in safe Rust? How?

unsafe fn

```rust
impl Vec {
    /// Sets the length of the vector to `new_len`.
    pub unsafe fn set_len(&mut self, new_len: usize) {
        self.len = new_len;
    }
}
```

Can only be called in an unsafe block!

But why is it possible in the first place?

UB AND INVARIANTS

- *Language Invariant*: something that is always true according to Rust
  - breaking a language invariant is (by definition) UB
  - e.g. `bool` is always `true` or `false`
  - e.g. all references are valid to dereference

UB AND INVARIANTS

- *Program Invariant*: something that is always true according to the *program spec*
  - e.g. the server must write results to the log before responding to the client
- *In the presence of* `unsafe`, breaking program invariants can break a language invariant which is UB

UB AND INVARIANTS

```rust
pub struct Vec<T> {
    buf: RawVec<T>, // `unsafe` in `RawVec`
    len: usize,
}
```

- Language invariant: no accesses to invalid memory
- Program invariant: `len` is no longer than `buf`
- Bad use of `Vec::set_len` violates program invariant => access memory out of bounds == UB.
- Not sufficient to just look in `unsafe` blocks!

UB AND INVARIANTS

`unsafe`: someone promises to uphold invariants!

"Promise" is called a *proof obligation*.

UB AND INVARIANTS

```rust
fn read_file(fd: i32, buf: &mut [u8]) {
    let len = buf.len();

    // `read_file` promises to respect buffer length
    unsafe {
        libc::read(fd, buf.as_mut_ptr(), len);
    }
}
```

```rust
// Caller of `set_len` promises to uphold `Vec` invariants!
pub unsafe fn set_len(&mut self, new_len: usize) {
    self.len = new_len;
}
```

DIFFERENT USES OF `unsafe`

Whose job to check?

- `unsafe { ... }` blocks
  - Enclosing function is responsible
- `unsafe fn`
  - Caller responsible when calling function
  - Impl. responsible when calling other `unsafe`
- `unsafe trait` and `unsafe impl`
  - Implementor is responsible

HOW TO PLAY WITH FIRE 🔥

SAFE ABSTRACTIONS

Idea: Abstraction hides `unsafe`

- Users of the abstraction have no way to cause UB
- Language features make unsafe parts inaccessible
  - Private struct/enum fields
  - Private modules/types
- Use `unsafe` to expose dangerous interfaces
- Can reason about correctness modularly

EXAMPLE: `Vec`

Using only *safe* methods of `Vec`, it is *impossible* to cause UB, even though `Vec` uses `unsafe` internally.

- The safe methods of `Vec` all uphold invariants.
- Methods that could violate invariants are `unsafe` (e.g. `set_len`)

EXAMPLE: READING FILES

```rust
fn main() -> std::io::Result<()> {
    // Open: call libc and OS. Safely!
    let file = File::open("foo.txt")?;
    let mut buf_reader = BufReader::new(file);
    let mut contents = String::new();
    // Read: call libc and OS. Safely!
    buf_reader.read_to_string(&mut contents)?;
    assert_eq!(contents, "Hello, world!");
    Ok(())

    // Close: call libc and OS. Safely!
}
```

`File`, `BufReader` are safe abstractions that uphold invariants about files, memory, etc.

CAUTION: FIRE IS HOT

INVARIANTS YOU DIDN'T KNOW ABOUT

- Variance
- Rust ABI
- Memory layout of types
  - Zero-sized types, uninhabited types
  - `#[repr(C)]` and `#[repr(packed)]`
- Type-based optimizations
- Reordering, memory coherence, and optimizations
- Many more in the Rustonomicon

PRACTICAL FIRE TWIRLING 101

EXAMPLE: `Vec`

- Caution: will ignore lots of concerns
- Can find real implementation on GitHub

DETOUR: RAW POINTERS

`*const T` and `*mut T`

- Like C pointers
- Not borrow checked, `unsafe` to dereference
- Utilities in `std::ptr`
- Helpful tools in libstd
  - `NonNull`

impl Vec

```rust
pub struct Vec<T> {
    buf: RawVec<T>,
    len: usize,
}

pub struct RawVec<T> {
    ptr: *mut T, // ptr to allocated space
    cap: usize, // amount of allocated space
}
```

impl Vec

```rust
pub fn new() -> Vec<T> {
    Vec {
        buf: RawVec::new(), // initially, no allocation
        len: 0,
    }
}
```

impl RawVec

```
pub fn new() -> Self {
    RawVec {
        ptr: ptr::null_mut(), // null ptr, safe to construct
        cap: 0,
    }
}
```

impl Vec

```rust
pub fn pop(&mut self) -> Option<T> {
    if self.len == 0 {
        None  // empty vector
    } else {
        unsafe {
            self.len -= 1;  // decrement length

            // raw ptr read at index into buffer, return
            Some(ptr::read(self.buf.ptr.add(self.len())))
        }
    }
}
```

impl Vec

```rust
pub fn push(&mut self, value: T) {
    // Are we out of space?
    if self.len == self.buf.cap() {
        self.buf.double(); // alloc more space
    }

    // put the element in the `Vec`
    unsafe {
        // compute address of end of buffer
        let end = self.buf.ptr.add(self.len);
        ptr::write(end, value); // write data to raw pointer
        self.len += 1; // increase length
    }
}
```

impl RawVec

```rust
pub fn double(&mut self) {
    unsafe {
        let new_cap = self.cap * 2 + 1; // new capacity

        // alloc more memory with system heap allocator
        let res = if self.cap > 0 {
            heap::realloc(NonNull::from(self.ptr).cast(),
                          self.cap, new_cap)
        } else {
            heap::alloc(new_cap)
        };
        // ...
    }
}
```

impl RawVec

```
pub fn double(&mut self) {
    unsafe {
        // ...
        match res {
            Ok(new_ptr) => { // update pointer and capacity
                self.ptr = res.unwrap().cast().into();
                self.cap = new_cap;
            }
            Err(AllocErr) => { // handle out of memory
                out_of_memory();
            }
        }
    }
}
```

OTHER `unsafe` TOOLS

- Type memory layout: `#[repr(...)]`
- Mixed-language projects
  - `extern fn`
  - Strings, variadic fns (e.g. `printf`), `extern` types
  - rust-bindgen
  - cbindgen

THANK YOU!

EXTRA RESOURCES

- The Rustonomicon
- Ralf Jung's Blog
- Alexis Beingessner
  - Notes on Type Layouts and ABI
  - Only in Rust
  - The Kinds of Implementation-Defined

EXTRA EXTRA RESOURCES

- Various IRLO discussions:
  - UB and uninitialized memory
  - What do “memory safety”/“thread safety” mean?
  - Taming UB in LLVM
- Guide to UB