Ownership, Pointers, and Memory

Advanced Systems Programming (M) 2023-2024 – Laboratory Exercise 5
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1 Introduction

The Advanced Systems Programming (H) course uses the Rust programming language to illustrate several advanced topics in systems programming. You're expected to learn the basics of programming in Rust as part of this course. This exercise reviews the basics of ownership, pointers, and memory management in Rust. **This is a formative exercise and is not assessed**, but note that the first assessed exercise, which will be available with Lecture 5, will be an essay question that relates to some of these topics.

2 Preliminaries: Unsafe Memory Usage in C

The sample program shown in Figure 1, at the end of this document, provides an example of unsafe memory usage in the C programming language. It contains at least seven bugs relating to memory safety. Read *and think about* the code to find the seven problems. Make sure you understand the cause of each of the bugs. You are not expected to compile and run the code, but rather think about how it works, and use your knowledge of C programming to reason about the way it uses memory. Discuss the code with lecturer or lab demonstrator to verify your understanding.

3 Memory Safety, Ownership, References, and Lifetimes in Rust

One of the goals of the Rust programming language is to make unsafe memory usage impossible, while not compromising on performance. Rust does this by tracking the ownership and lifetime of data, and having the compiler automatically insert the calls to free memory when data goes out of scope, and to prohibit programs that don't maintain clear ownership of data. Read the sections of the online Rust book explaining ownership, lifetimes, and smart pointers:

- `https://doc.rust-lang.org/book/ch04-00-understanding-ownership.html`
- `https://doc.rust-lang.org/book/ch10-03-lifetime-syntax.html`
- `https://doc.rust-lang.org/book/ch15-00-smart-pointers.html`

The following programs demonstrate some memory safety and ownership features of the language. Review them carefully, answer the associated questions, and then discuss your answers with the lecturer or lab demonstrator.

Example 1: The following Rust program does not compile. Review and try to compile the program. Explain what is the problem with the code and why it does not compile. Finally, fix the program so that it compiles and runs correctly. Consider when is the memory allocated to the vector, `v`, when is it freed, and how ownership of the vector varies as the program executes. Explain what is the meaning of the `'a` specifiers in the definition of the `Person` structure.

```
#[derive(Debug)]
struct Person<'a> {
    name : &'a str,
    role : &'a str
}
```

```
fn print_employees(employees: Vec<Person>) {
    for e in &employees {
      println!("{:?}", e);
    }
}

fn main() {
    let mut v = Vec::new();
    v.push(Person{name : "Alice", role : "Manager"});
    v.push(Person{name : "Bob"  , role : "Sales"});
    v.push(Person{name : "Carol", role : "Programmer"});

    print_employees(v);

    println!("v.len() = {}", v.len());
}
```

Example 2: The following Rust program also does not compile. Review and try to compile the program. Explain what is the problem with the code and why it doesn't compile. What memory safety problem is the compiler avoiding by prohibiting this code from compiling?

```
fn smallest(v: &[i32]) -> &i32 {
    let mut s = v[0];
    for r in &v[1..] {
        if *r < s {
            s = *r;
        }
    }
    &s
}

fn main() {
    let n = [12, 42, 6, 8, 15, 24];
    let s = smallest(&n);
    println!("{}", s);
}
```

Example 3: The following Rust program shows how to allocate a `struct` on the heap. It should compile and run, and will print that the `area = 8`. This program demonstrates that `Box<T>` implements the `Deref` trait, making it possible to obtain a reference to its contents. This reference can then be stored in a structure that expects an `&T` reference. Explain at what point will the compiler insert calls to deallocate the heap memory allocated to the two boxes. Implement the `std::ops::Drop` trait for `Point` to print a message when the data is dropped to confirm your understanding.

```
struct Point {
    x : f32,
    y : f32
}

struct Rectangle<'a> {
    ul : &'a Point,
    br : &'a Point
}

impl<'a> Rectangle<'a> {
    fn area(&self) -> f32 {
        let w = self.br.x - self.ul.x;
        let h = self.ul.y - self.br.y;
        w * h
    }
}
```

```
fn main() {
    let ul = Box::new(Point{x : 3.0, y : 8.0});
    let br = Box::new(Point{x : 5.0, y : 4.0});
    let rect = Rectangle{ul : &ul, br : &br};
    let a = rect.area();
    println!("area = {}", a);
}
```

Example 4: The following Rust program does not compile. Review the code and try to compile the program. Explain what is the problem with the code, thinking in terms of what data is moved, what data is borrowed, and the rules around multiple references. Explain why it is correct that the program does not compile.

```
fn main() {
    let v = vec![4, 8, 19, 27, 34, 10];
    let r = &v;

    let aside = v;

    println!("{}", r[0]);
    println!("{}", aside[0]);
}
```

Example 5: The following Rust program *does* compile. When run, it will print that `x=3` and `y=5`. Thinking in terms of ownership of data, what data is moved and when it moves, and the rules around multiple references, explain why this program compiles and runs.

```
struct Point {
    x : f32,
    y : f32
}

fn main() {
    let p = Point{x: 3.0, y : 5.0};
    let x = &p.x;
    let y = &p.y;
    println!("x={}", x);
    println!("y={}", y);
}
```

4 Resource Management and State Machines

In addition to safely managing memory, the ownership system in Rust can be used to manage the lifetime of other resources. In the simplest case, this can be used to ensure that a resource is not referenced or accessed after it has been destroyed. For example, a `trait` representing a file or a network connection might implement a function `close()` defined as follows:

```
pub fn close(self) -> Result<(), Error> {
  ...
}
```

Note that this function is passed `self` by value, rather than by reference, and so takes ownership of the object on which it is called. Further it does not return `self`, meaning that the lifetime of the object ends when the function returns. That is, the `close()` function consumes the file it is closing, meaning it will be inaccessible after the call to `close()`. This is a strong guarantee: the compiler will enforce that code cannot be written to access the file after it is closed (or, has potentially been closed). The first part of the blog post at `https://yoric.github.io/post/rust-typestate/` describes this pattern in more detail - read it, and think about the code samples shown, their behaviour, and the limitations of the technique.

Lecture 4 discussed various ways of implementing state machines in Rust. These keep track of the state of a resource, and only allow particular operations when the resource is in the correct state. For example, it's possible to track the state of a Socket representing a TCP connection, and only allow data to be sent when it is connected. The second part of the blog post at `https://yoric.github.io/post/rust-typestate/` discusses an alternative way to implement state machines, using the idea of *phantom types* and type parameter to represent states in the system. Read this blog post and think about the design pattern discussed. What is a phantom type? How much storage space does a phantom type, encoded as a `struct` with no fields, use? Is a `struct` with a phantom type as a type parameter represented differently in memory than a `struct` without such a parameter? Does this approach affect the efficiency of the generated code?

The `struct`-based approach to managing state machines, described in Lecture 4, is further discussed in the post at `https://blog.systems.ethz.ch/blog/2018/a-hammer-you-can-only-hold-by-the-handle.html`. You should read this blog post, to ensure you understand the approach and its implementation in Rust.

Think about when might you use a phantom type to represent states rather than the `struct` or `enum`-based approaches discussed in the lecture? What is the trade-off between the different approaches? Discuss the code during the labs if you are unsure how it works. Try to get the code from the second blog post working on your own machine. Think about cases where similar patterns could be used to enforce correct behaviour in the code you have previously written. Discuss your results and ideas with the lecturer or lab demonstrator.

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```c
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

// There are at least 7 bugs relating to memory on this snippet.
// Find them all!

// Vec is short for "vector", a common term for a resizable array.
// For simplicity, our vector type can only hold ints.
typedef struct {
  int* data;     // Pointer to our array on the heap
  int  length;   // How many elements are in our array
  int  capacity; // How many elements our array can hold
} Vec;

Vec* vec_new() {
  Vec vec;
  vec.data = NULL;
  vec.length = 0;
  vec.capacity = 0;
  return &vec;
}

void vec_push(Vec* vec, int n) {
  if (vec->length == vec->capacity) {
    int new_capacity = vec->capacity * 2;
    int* new_data = (int*) malloc(new_capacity);
    assert(new_data != NULL);

    for (int i = 0; i < vec->length; ++i) {
      new_data[i] = vec->data[i];
    }

    vec->data = new_data;
    vec->capacity = new_capacity;
  }

  vec->data[vec->length] = n;
  ++vec->length;
}

void vec_free(Vec* vec) {
  free(vec);
  free(vec->data);
}

void main() {
  Vec* vec = vec_new();
  vec_push(vec, 107);

  int* n = &vec->data[0];
  vec_push(vec, 110);
  printf("%d\n", *n);

  free(vec->data);
  vec_free(vec);
}
```

Figure 1: Unsafe Memory Usage in C. The sample program contains at least seven memory related bugs – find them. The example is taken from `http://cs242.stanford.edu/f18/lectures/05-1-rust-memory-safety.html`, which also has the solution.