ECE 421

Lecture 7

Memory Safety in Rust & C

Introduction

There are two program properties:

Memory safety

- Memory pointers point to valid memory.
- A memory unsafe program may crash.

Memory Containment

- Memory does not leak.
- A leaky program may eventually run out of memory.

Introduction

- In CG languages (like Java and Python) memory safety is guaranteed within the language runtime.
- In non-GC languages, like C, C++ and Rust, these memory properties must either be guaranteed by the compiler via static analysis (Rust’s borrow checker),
- or they must be carefully managed by the programmer at runtime (malloc/free, new/delete).

Example

- The following example provides an implementation of a vector library (or resizable array) specialized for integers.
- It contains at least 7 bugs relating to the properties of memory safety and containment.

Please note: this is written in C and I don’t really write C.

Example

```
typedef struct {
  int* values;   int  len;   int  capacity;
}Vec;
Vec* vec_new() {
  Vec vec;   vec.values = NULL;   vec.len = 0;
  vec.capacity = 0;   return &vec;
}
void vec_insert(Vec* vec, int n) {
  if (vec->len == vec->capacity) {
    int new_capacity = vec->capacity * 2;
    int* new_values = (int*) malloc(new_capacity);
    assert(new_values != NULL);
    for (int i = 0; i < vec->len; ++i) {
      new_values[i] = vec->values[i];    }
    vec->values = new_values;
    vec->capacity = new_capacity;   }
  vec->values[vec->len] = n;
  ++vec->len; }
```

Example

```
void vec_deallocate(Vec* vec) {
  free(vec);
  free(vec->values);
}
void main() {
  Vec* vec = vec_new();
  vec_insert(vec, 107);

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

  free(vec->values);
  vec_deallocate(vec);
}
```

Issues

1. *vec_new*: This is a dangling pointer. the stack frame is deallocated when the function returns, so any subsequent use of the pointer is invalid.
2. *vec_new*: initial capacity is 0. When capacity doubles, 2 * 0 = 0.
3. *vec_insert*: incorrect call to malloc. We need to malloc(sizeof(int) * new_capacity).
4. *vec_insert*: missing free on resize.
5. *vec_deallocate*: incorrect ordering on the free statements.
6. *main*: double free of vec->values.
7. *main*: invalid initialization of n.

Dangling pointer

- A pointer pointing to a memory location that has been deleted (or freed) is called dangling pointer.
- Here are two examples where Pointer acts as dangling pointer

1. De-allocation of memory

```
// Deallocating a memory pointed by ptr causes
// dangling pointer
#include <stdlib.h>
#include <stdio.h>
int main()
{
    int *ptr = (int *)malloc(sizeof(int));
    // After free call, ptr becomes a dangling pointer
    free(ptr);
    // No more a dangling pointer
    ptr = NULL;
}
```

Dangling pointer

2. Function Call

```
// The pointer pointing to local variable becomes
// dangling when local variable is not static.
#include<stdio.h>
int *fun()
{
    // x is local variable and goes out of
    // scope after an execution of fun() is over.
    int x = 5;
    return &x;
}
int main()
{
    int *p = fun();
    fflush(stdin);
    // p points to something which is not valid anymore
    printf("%d", *p);
    return 0;
}
```

Issues

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3. *vec_insert*: incorrect call to malloc. We need to malloc(sizeof(int) * new_capacity).
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7. *main*: invalid initialization of n.

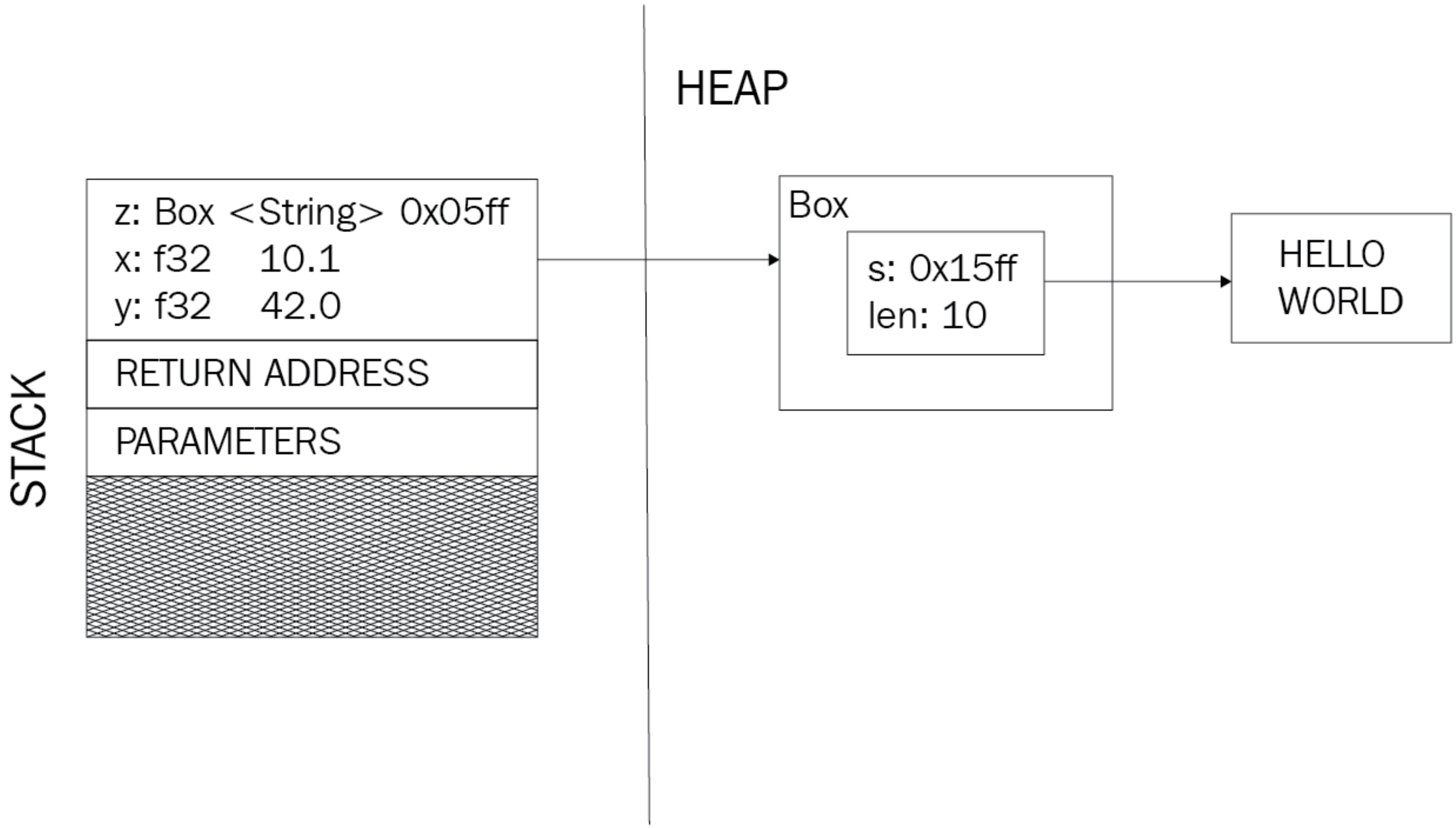
Example

- If we naively translate the previous C code:

```
struct Vec2 {
    values: Box<[isize]>,
    len: usize,
    capacity: usize
}
impl Vec2 {
    fn new() -> &Vec2 {
        let v = Vec2 {
            values: Box::new([]),
            len: 0,
            capacity: 0
        };
        return &v;
    }}
fn main () {}
```

What on earth is a Box?

What on earth is a Box?



Example

- Here, if we naively translate the previous C code, this fails to compile:

```
error[E0106]: missing lifetime specifier
 --> v.rs:8:17
  |
8 |     fn new() -> &Vec2 {
  |                 ^ expected lifetime parameter
  |
  = help: this function's return type contains a borrowed
value, but there is no value for it to be borrowed from
  = help: consider giving it a 'static lifetime
```

Example

- Rust can identify the dangling stack pointer issue.
- It analyzes the type signature of the function.
- Since the function takes no references as input, it's impossible to return a reference as output.
- How can we fix this error?

```
impl Vec2 {
    fn new() -> Vec2 {
        let v = Vec2 {
            values: Box::new([0]),
            len: 0,
            capacity: 1
        };
        return v;
    }}
```

Example

- Note that the capacity issue is a logic error that must be identified by the programmer.
- Next, we implement the insert method:

Example

```
fn vec_insert(&mut self, n: isize) {
    if self.len == self.capacity {
        let new_capacity = self.capacity * 2;
        let mut new_value = unsafe {
            let ptr = Heap::default()
                .alloc(Layout::array::<isize>
                (new_capacity).unwrap())
               .unwrap() as *mut isize;
            Box::from_raw(slice::from_raw_parts_mut(ptr,
               new_capacity))
        };
        for i in 0..self.length {
            new_value[i] = self.values[i];
        }
        self.values = new_value;
        self.capacity = new_capacity;
    }
    self.values[self.len] = n;
    self.len += 1;
}
```

Example

- This method compiles and works correctly.
- It does not require an explicit free.
- Rust will automatically deallocate the old value of values when it is reassigned
- The programmer does not have to free allocated memory, this eliminates both the associated memory leaks as well as double frees.

Memory Allocation in Rust

- All memory allocations happen either implicitly on the stack by declaring a value
- Or explicitly on the heap when using Box or any pointer type derived from it

```
struct Point { x: f32, y: f32 }
let p: Box<Point> = Box::new(Point{ x: 0.1, y: 0.2 });
```

- Rust determines the size of Point and does the appropriate malloc(sizeof(Point)).

Memory Deallocation in Rust

- We do not have to implement the vec_deallocate function.
- Rust automatically generates the appropriate destructors.

Initialization Invalidation

- Note that the following main function:

```
fn main() {
    let mut vec: Vec2 = Vec2::new();
    vec.insert(107);
    let n: &isize = &vec.data[0];
    vec.insert(110);
    println!("{}", n);
}
```

- Fails with the following error:

```
error[E0502]: cannot borrow `vec` as mutable because
`vec.data[..]` is also borrowed as immutable
  --> v.rs:50:5
   |
49 |     let n: &isize = &vec.data[0];
   |                      ----------- immutable borrow
occurs here
```

To sum up..

- The guarantees provided by Rust helped us fix memory-related errors in C.
- No matter how large your code base, Rust enforces these guarantees everywhere.
- All this, of course, comes at the price of fighting with Rust’s borrow checker.

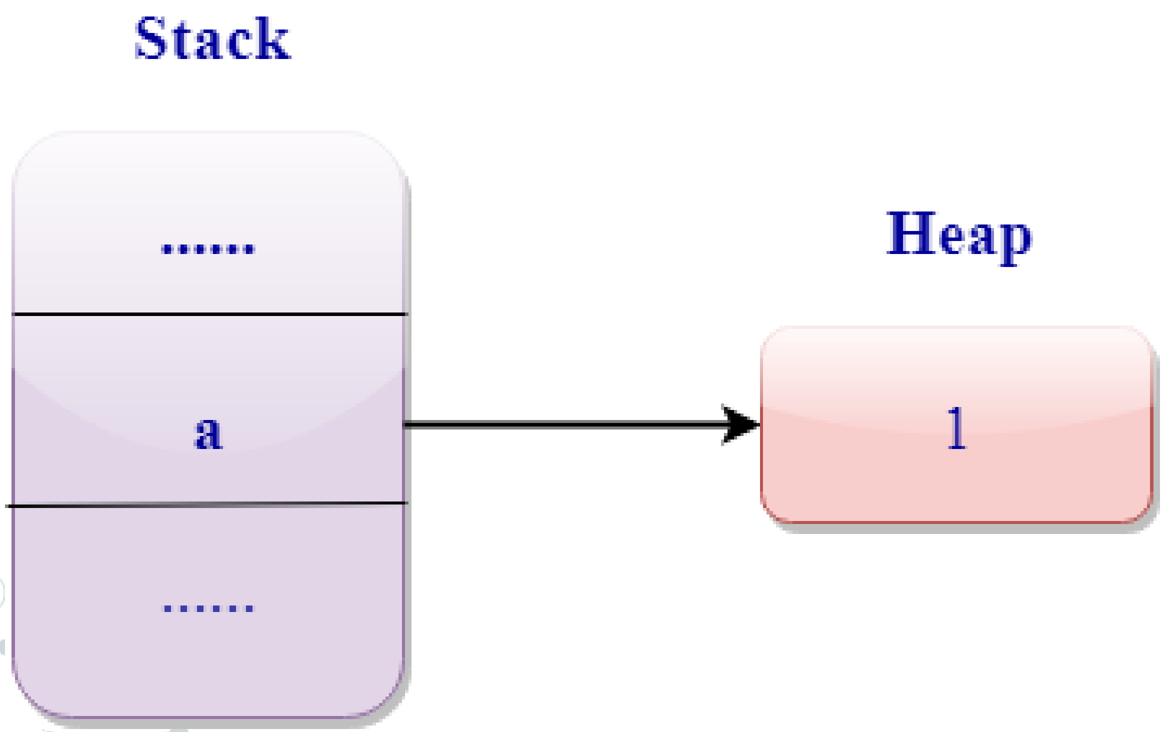
Box<T>

- Box<T> is a smart pointer that points to the data which is allocated on the heap of type T.
- Box<T> is an owned pointer.
- Boxes do not have a performance overhead, other than storing the data on the heap.
- When the Box goes out of the scope, then the destructor is called to release the memory.

```
fn main()
{
  let a = Box :: new(1);
  print!("value of a is : {}",a);
}
Output: value of a is : 1
```

Box<T>

```
fn main()
{
  let a = Box :: new(1);
  print!("value of a is : {}",a);
}
Output: value of a is : 1
```



Cons List “Construct function”

- Cons list is a data structure which is used to construct a new pair from the two arguments, and this pair is known as a List.
- Cons is a variant of the List enum. It's saying there are two possible cases of a linked list - an empty list or a head consisting of a u32 and a ~List

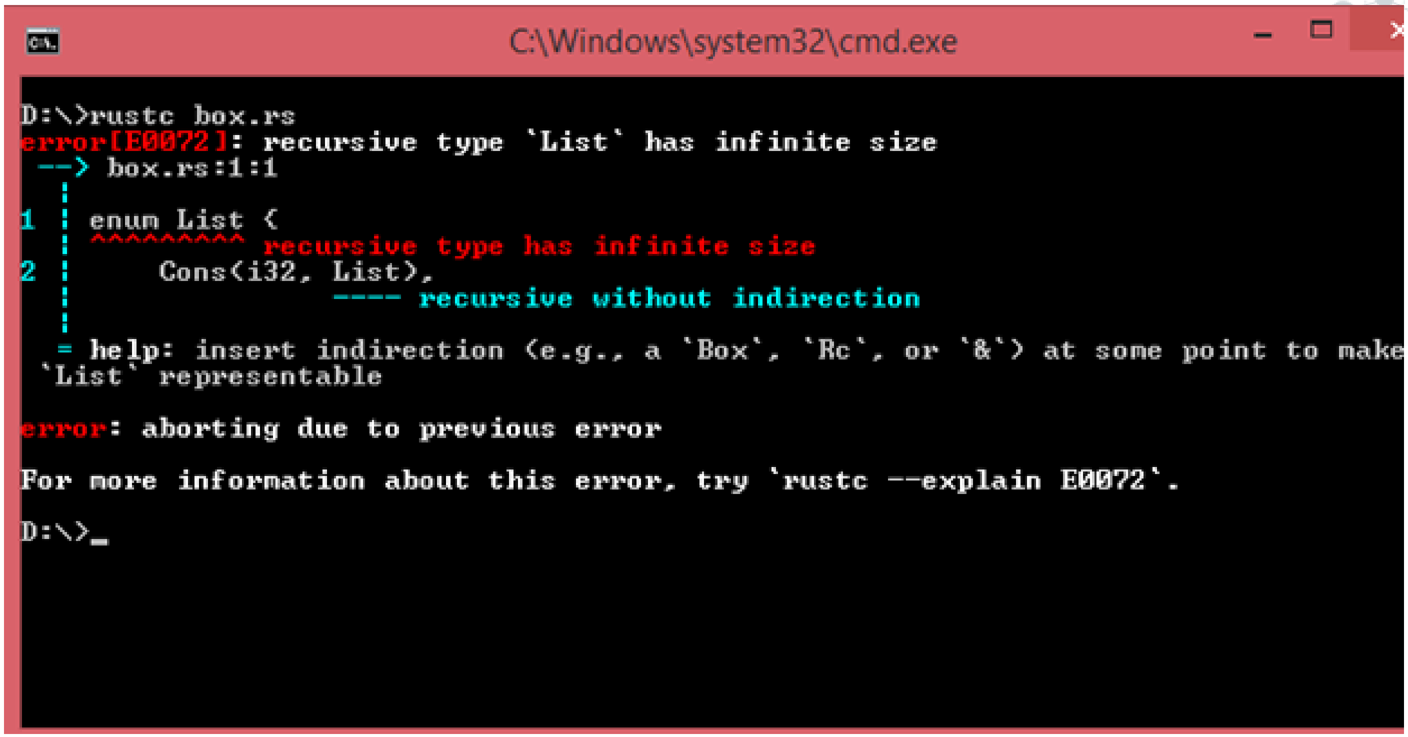
```
enum List
{
    cons(i32, List),
    Nil,
}
```

Cons List "Construct function"

```
 enum List {
    Cons(i32, List),
    Nil,
}
use List::{Cons, Nil};
fn main()
{
  let list = List::Cons(1,Cons(2,Cons(3,Nil)));
  for i in list.iter()
  {
    print!("{}",i);
  }
}
```

Cons List “Construct function”

- Output:



- Rust is not able to find out how much space is required to store the List value. The problem of an infinite size can be overcome by using the Box<T>.

Using Box<T> to get the size of a recursive type

```
 #[derive(Debug)]
enum List {
    Cons(i32, Box<List>),
    Nil,
}
use List::{Cons, Nil};
fn main()
{
  let list =
Cons(1,Box::new(Cons(2,Box::new(Cons(3,Box::new(Nil))))));

    print!("{:?}",list);

}
Output:
Cons(1, Cons(2, Cons(3, Nil)))
```

How do you know if a Rust variable is allocated on the heap?

- If a variable has type Box<T>, then it’s a pointer to some memory on the heap.

- Are there other types that are always on the heap?

1. Vec<T> (an array on the heap)
2. String (a string on the heap)
3. Box<T> (just a pointer)

Just a pointer, Rust does not really understand what it points to.