CMSC 330: Organization of Programming Languages

Ownership, References, and Lifetimes in Rust

Rust: GC-less Memory Management, Safely

- Rust's heap memory managed **without GC**
- Type checking ensures **no dangling pointers** or **buffer overflows**
  - unsafe idioms are disallowed
- Key features that ensure safety: **ownership** and **lifetimes**
  - Data has a single owner. Immutable aliases OK, but mutation only via owner or single mutable reference
  - How long data is alive is determined by a lifetime

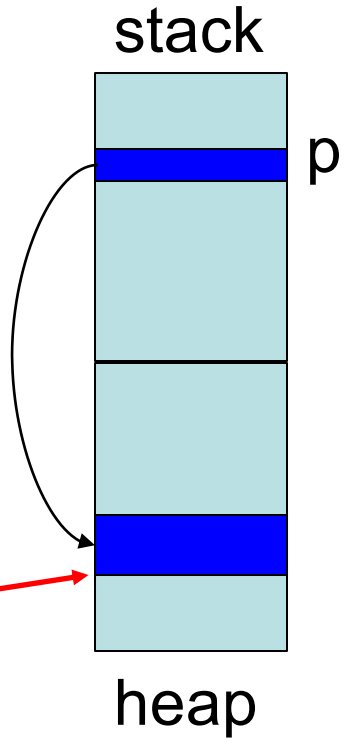
Memory: the Stack and the Heap

- The stack
  - constant-time, automatic (de)allocation
  - Data size and lifetime must be known at compile-time
    - Function parameters and locals of known (constant) size
- The heap
  - Dynamically sized data, with non-fixed lifetime
    - Slightly slower to access than stack; i.e., via a pointer
  - **GC**: automatic deallocation, adds space/time overhead
  - **Manual** deallocation (C/C++): low overhead, but non-trivial opportunity for **devastating bugs**
    - Dangling pointers, double free – instances of memory corruption

Memory: the Stack and the Heap

```
// C
char *p = malloc(10)
…
free(p);
```

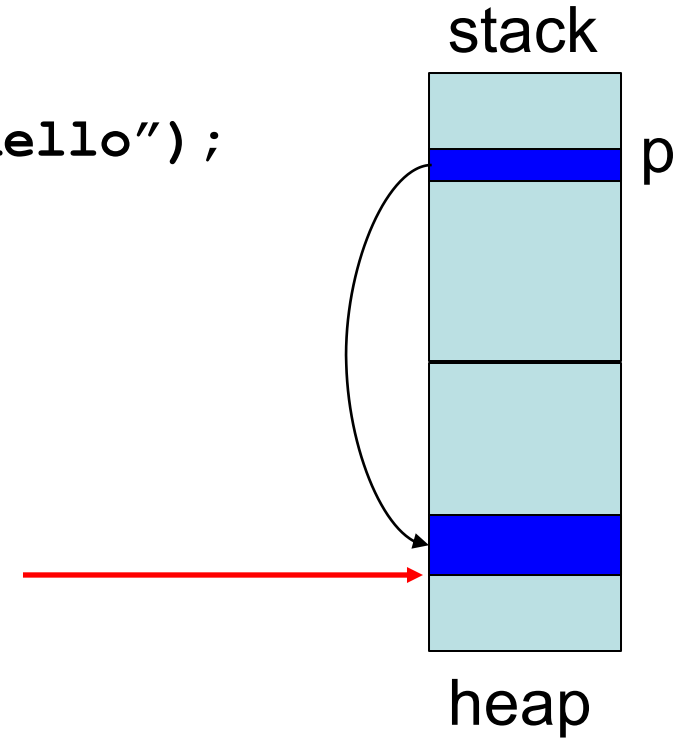
```
// Java
String p = new String(”rust");
…
p = null;//GC will collect later
```



p is deleted from stack when the function terminates

Memory: the Stack and the Heap

```
// Rust
let p = String::from("hello");
…
```



- Deleted when the owner p is out of scope.
- No manual free, no GC

p is deleted from stack when the function terminates

Rules of Ownership

1. Each value in Rust has a variable that's its owner
2. There can only be one owner at a time
3. When the owner goes out of scope, the value will be dropped (freed)

```
{ let mut s = String::from("hello"); //s is the owner
  s.push_str(", world!");
  println!("{}", s);
} //s's data is freed by calling s.drop()
```

`String`: Dynamically sized, mutable data

Assignment Transfers Ownership

- By default, an assignment *moves* data

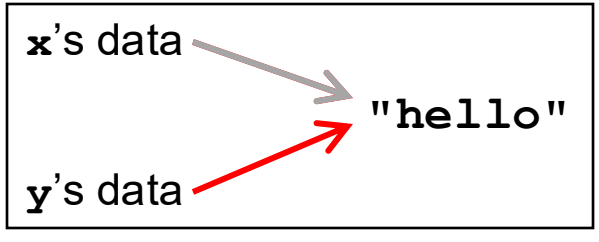
```
let x = String::from("hello");
let y = x; //x moved to y
```

- A move leaves only one owner: **y**

```
println!("{}, world!", y); //ok
println!("{}, world!", x); //fails
```

- Why? Both **x** and **y** may point to the same underlying data

Move prevents double ***free****, or use-after-****free***



Copy Trait

- Primitives do not transfer ownership on assignment
  - `i32`, `char`, `bool`, `f32`, tuples of these types, etc.

```
let x = 5;
let y = x;
println!("{} = 5!", y); //ok
println!("{} = 5!", x); //ok
```

- Why? These derive the `Copy` trait
  - Doing so says that an assignment copies the entire object

Traits

- A Trait is a way of saying that a type has a particular property
  - **`Copy`**: objects with this trait do *not* transfer ownership on assignment
    - instead, assignment copies all of the object data

- Another way of using traits: to indicate functions that a type is must implement (more later)
  - Like Java interfaces
  - Example: **`Deref`** built-in trait indicates that an object can be dereferenced via **`*`** op; compiler calls object's **`deref`**() method

Use clone() to make explicit copies

- Objects may be explicitly cloned
  - Avoids loss of ownership, but at the cost of a copy

```
let x = String::from("hello");
let y = x.clone(); //x ownership not moved
println!("{}, world!", y); //ok
println!("{}, world!", x); //ok
```

Ownership Transfer in Function Calls

```
fn main() {
  let s1 = String::from("hello");
  let s2 = id(s1);    //s1 moved to arg
  println!("{}",s2); //id's result moved to s2
  println!("{}",s1); //fails
}

fn id(s:String) -> String {
 s // s moved to caller, on return
}
```

- On a call, ownership passes from:
  - argument to called function's parameter
  - returned value to caller's receiver

References and Borrowing

- Create an alias by making a reference
  - An explicit, non-owning pointer to the original value
  - Called borrowing. Done with `&` operator
- References are immutable by default (can override)

```
fn main() {
 let s1 = String::from("hello");
 let len = calc_len(&s1); //lends reference
 println!("the length of '{}' is {}",s1,len);
}
fn calc_len(s: &String) -> usize {
 s.push_str("hi"); //fails! refs are immutable
 s.len()     // s dropped; but not its referent
}
```

Quiz 1: Owner of str's data at *HERE* ?

```
fn foo(str:String) -> usize {
  let x = str;
  let y = &x;
  let w = &y;
  // HERE
}
```

A. x
B. y
C. z
D. w

`let w = &y vs. let w = y;`

There are a few other types I'd consider "primitive":

- Immutable references (&T)
- Mutable references (&mut T)
- Raw pointers (*const T / *mut T)

Immutable references always implement Copy, mutable references never implement Copy, and raw pointers always implement Copy:

Quiz 1: Owner of str's data at *HERE* ?

```
fn foo(str:String) -> usize {
  let x = str;
  let y = &x;
  let w = &y;
  // HERE
}
```

A. x

B. y

C. z

D. w

Rules of References

1. At any given time, you can have *either* but not both of
   - One mutable reference
   - Any number of immutable references

2. References must always be valid (pointed-to value not dropped)

Borrowing and Mutation

- Make immutable references to mutable values
  - Shares read-only access through owner and borrowed references
    - Same for immutable values
  - Mutation disallowed on original value until borrowed reference(s) dropped

```
{ let mut s1 = String::from("hello");
  { let s2 = &s1;
    println!("String is {} and {}",s1,s2); //ok
    s1.push_str(" world!"); //disallowed
  } //drops s2
  s1.push_str(" world!"); //ok
  println!("String is {}",s1);}//prints updated s1
```

Mutable references

- To permit mutation via a reference, use **`&mut`**
  - Instead of just **`&`**
  - But only OK for mutable variables

```
let mut s1 = String::from("hello");
{ let s2 = &s1;
  s2.push_str(" there");//disallowed; s2 immut
} //s2 dropped
let s3 = &mut s1; //ok since s1 mutable
s3.push_str(" there"); //ok since s3 mutable
println!("String is {}",s3); //ok
```

Quiz 2: What does this evaluate to?

```
{ let mut s1 = String::from("Hello!");
    {
      let s2 = &s1;
      s2.push_str("World!");
      println!("{}", s2)
    }
}
```

A. “Hello!”
B. “Hello! World!”
C. Error
D. “Hello!World!”

Quiz 2: What does this evaluate to?

```
{ let mut s1 = String::from("Hello!");
    {
      let s2 = &s1;
      s2.push_str("World!");
      println!("{}", s2)
    }
}
```

A. “Hello!”

B. “Hello! World!”

C. Error; s2 is not mut

D. “Hello!World!”

Quiz 3: What is printed?

```
fn foo(s: &mut String) -> usize{
    s.push_str("Bob");
    s.len()
}
fn main() {
    let mut s1 = String::from("Alice");
    println!("{}",foo(&mut s1))
}
```

A. 0

B. 8

C. Error

D. 5

Quiz 3: What is printed?

```
fn foo(s: &mut String) -> usize{
    s.push_str("Bob");
    s.len()
}
fn main() {
    let mut s1 = String::from("Alice");
    println!("{}",foo(&mut s1))
}
```

A. 0

B. 8

C. Error

D. 5

Ownership and Mutable References

- Can make only one mutable reference
- Doing so blocks use of the original
  - Restored when reference is dropped

```
let mut s1 = String::from("hello");
{ let s2 = &mut s1; //ok
  let s3 = &mut s1; //fails: second borrow
  s1.push_str(" there"); //fails: second borrow
} //s2 dropped; s1 is first-class owner again
s1.push_str(" there"); //ok
println!("String is {}",s1); //ok
```

implicit borrow
(**self** is a reference)

But: see next slide

Update: Non Lexical Lifetimes (NLL)

- Rust has been updated to support lifetimes that end before the surrounding scope:
  - http://blog.pnkfx.org/blog/2019/06/26/breaking-news-non-lexical-lifetimes-arrives-for-everyone/

```
let mut s1 = String::from("hello");
{ let s2 = &mut s1; //ignored - never used
  let s3 = &mut s1; //ignored - never used
  s1.push_str(" there"); //OK!
  s2.push_str(" there"); //fails - 2 mutable refs
} //s2 dropped; s1 is first-class owner again
s1.push_str(" there"); //ok
println!("String is {}",s1); //ok
```

The * Operator

- Given a value of type ***T&*** (or ***T&mut***) use the `*` operator to read or write its underlying contents

```
let mut x = 2;
let mut y = 3;
let mut r = &mut x;
*r = 4;
r = &mut y;
*r = 5;
```

  - Note two uses of **`mut`** for **`r`**, with different meanings!

Immutable and Mutable References

- Cannot make a mutable reference if immutable references exist
  - Holders of an immutable reference assume the object will not change!

```
let mut s1 = String::from("hello");
{ let s2 = &s1; //ok: s2 is immutable
  let s3 = &s1; //ok: multiple imm. refs allowed
  let s4 = &mut s1; //fails: imm ref already
} //s2-s4 dropped; s1 is owner again
s1.push_str(" there"); //ok
println!("String is {}",s1); //ok
```

Aside: Generics and Polymorphism

- Rust has support like that of Java and OCaml
  - Example: The **`std`** library defines **`Vec<T>`** where **`T`** can be instantiated with a variety of types
    - **`Vec<char>`** is a vector of characters
    - **`Vec<&str>`** is a vector of string slices

- You can define polymorphic functions, too
  - Rust:
  - Java:
  - Ocaml:

```
fn id<T>(x:T) -> T { x }
```

```
static <T> T id(T x) { return x; }
```

```
let id x = x
```

- More later…

Lifetimes: Avoiding Dangling References

- References must always be to valid memory
  - Not to memory that has been dropped

```
fn main() {
  let ref_invalid = dangle();
  println!("what will happen … {}",ref_invalid);
}
fn dangle() -> &String {
  let s1 = String::from("hello");
  &s1
} // bad! s1's value has been dropped
```

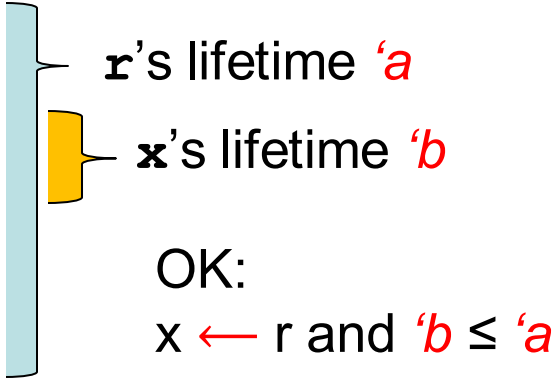
  - Rust will disallow this using a concept called lifetimes
    - A lifetime is a type-level parameter that names the scope in which the data is valid

Lifetimes: OK Usage

- Lifetime corresponds with scope

```
{
  let r = 5;
  {
    let x = &r;
    println!("r: {}",r); //ok
  }

}
```

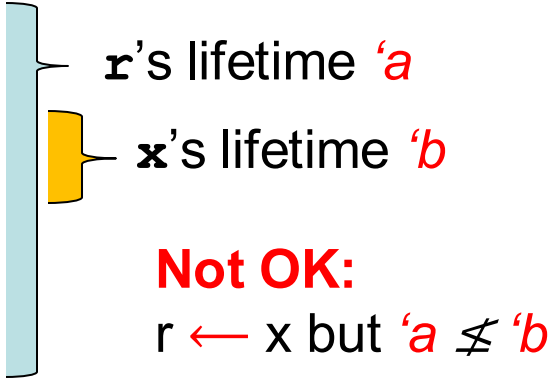


- Variable **x** in scope while **r** is
  - A **lifetime** is a *type variable* that identifies a scope
  - **r**'s lifetime 'a exceeds **x**'s lifetime 'b

Lifetimes: Preventing Dangling Refs

- Slightly changing the example

```
{
  let r; // deferred init
  {
    let x = 5;
    r = &x;
  }
  println!("r: {}",r); //fails
}
```



- Variable **x** goes out of scope while **r** still exists
  - **r**'s lifetime ‘a exceeds **x**'s lifetime ‘b so not safe to assign **x** to **r**

Quiz 4: What is printed?

```
{ let mut s = &String::from("dog");
      {
          let y = String::from("hi");
          s = &y;
      }
      println!("s: {}",s);
}
```

A. dog
B. hi
C. Error – y is immutable
D. Error – y dropped while still borrowed

Quiz 4: What is printed?

```
{ let mut s = &String::from("dog");
      {
          let y = String::from("hi");
          s = &y;
      }
      println!("s: {}",s);
}
```

A. dog

B. hi

C. Error – y is immutable

D. Error – y dropped while still borrowed

Lifetimes and Functions

- Lifetime of a reference not always explicit
  - E.g., when passed as an argument to a function

String slice
(more later)

```
fn longest(x:&str, y:&str) -> &str {
  if x.len() > y.len() { x } else { y }
}
```

  - What could go wrong here?

```
{ let x = String::from("hi");
  let z;
  { let y = String::from("there");
    z = longest(&x,&y); //will be &y
  } //drop y, and thereby z
  println!("z = {}",z);//yikes!
}
```

Lifetime Parameters

- Each reference to a value of type *t* has a lifetime parameter
  - `&t` (and `&mut t`) – lifetime is implicit
  - `&'a t` (and `&'a mut t`) – lifetime `'a` is explicit
- Where do the lifetime names come from?
  - When left implicit, they are generated by the compiler
  - Global variables have lifetime `'static`
- Lifetimes can also be generic

```
fn longest<'a>(x:&'a str, y:&'a str) -> &'a str {
  if x.len() > y.len() { x } else { y }
}
```

  - Thus: `x` and `y` must have the same lifetime, and the returned reference shares it

Lifetimes FAQ

- When do we use explicit lifetimes?
  - When more than one var/type needs the same lifetime (like the `longest` function)

- How do I tell the compiler exactly which lines of code lifetime `'a` covers?
  - You can't. The compiler will (always) figure it out

Lifetimes FAQ

- How does lifetime subsumption work?
  - If lifetime `'a` is longer than `'b`, we can use `'a` where `'b` is expected; can require this with `'b: 'a`.
    - Permits us to call `longest(&x,&y)` when `x` and `y` have different lifetimes, but one outlives the other
  - Just like subtyping/subsumption in OO programming

- Can we use lifetimes in data definitions?
  - Yes; we will see this later when we define **`structs`**, **`enums`**, etc.

Recap: Rules of References

1. At any given time, you can have *either* but not both of
   - One mutable reference
   - Any number of immutable references

2. References must always be valid
   - A reference must never outlive its referent