CMSC 330: Organization of Programming Languages

Box Smart Pointer, Trait Objects, Interior Mutability

Box<T> Smart Pointers

- `Box<T>` values point to heap-allocated data
  - The `Box<T>` value (the pointer) is on the stack, while its pointed-to `T` value is allocated on the heap
  - Has `Deref` trait – can be treated like a reference
    - More later
  - Has `Drop` trait – will drop its data when it dies

- Uses?
  - Reduce copying (via an ownership move)
  - Create dynamically sized objects
    - Particularly useful for recursive types

Example: Linked List

- Naïve attempt doesn't work
  - Compiler complains that it can't know the size of **`List`**
  - The **`Cons`** case is "inlined" into the **`enum`**
    - Since a **`List`** is recursive, it could be basically any size

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

- Use a **`Box`** to add an indirection
  - Now the size is fixed
    - **`i32`** + size of pointer
      - **`Nil`** tag smaller

```
enum List {
  Nil,
  Cons(i32,Box<List>)
}
```

Creating a LinkedList

```
enum List {
  Nil,
  Cons(i32,Box<List>)
}

use List::{Cons, Nil};

fn main() {
  let list = Cons(1,
    Box::new(Cons(2,
      Box::new(Nil))));
  … // data dropped at end of scope
}
```

Deref Trait

- If `x` is an `int` then `&x` is a `&{int}`
  - Can use `*` operator to dereference it, extracting the underlying value
    - `*(&x) == x`
- Can use `*` on `Box<T>` types
  - `Deref` trait requires `deref(&self) -> &T` method
  - So that `*x` translates to `*(x.deref())`

- `deref` returns type `&T` and not `T` so as not to relinquish ownership from inside the `Box` type

Deref Coercion

- The Rust compiler automatically inserts one or more calls to **`x.deref()`** to get the right type
  - When **`&T`** required but value **`x : U`** provided, where **`U`** implements **`Deref`** trait
  - In particular, at function and method calls

- Also a **`DerefMut`** trait, for when object is mutable
  - **`Deref`** coercion works with this too (see Rust book)

Example

```
fn hello(x:&str) {
    println!("hello {}",x);
}
fn main() {
    let m = Box::new(String::from("Rust"));
    hello(&m); //same as hello(&(*m)[..]);
}
```

- `&m` should have type `&str` to pass it to `hello`
- So, compiler calls `m.deref()` to get `&String`, and then `deref()` again to get `&str`

Drop Trait

- Provides the method **`fn drop(&mut self)`**
  - Called when the value implementing the trait goes out of scope
  - Should be used to free the underlying resources, e.g., heap memory

- May not call drop method manually
  - Would lead to a **double free** when Rust calls the method again at the end of a scope
  - Can call **`std::mem::drop`** function in some circumstances

Size Matters

- Recall **`Summarizable`**

```
pub trait Summarizable {
  fn summary(&self) -> String {
    String::from("none")
  }
}

impl Summarizable for i32 {…}
```

- Let's make a general summary-printing function
- First attempt: **`fn print_summary(s: Summarizable) {…}`**
  - This means the caller *moves* (or copies, if s is **`Copy`**) the argument to the function when calling it (**`s`** is not a reference)
  - This means the *data* in the argument needs to be moved/copied
  - How many bytes long is the data? Don't know; won't work

Still Not Right

- Recall **`Summarizable`**

```
pub trait Summarizable {
  fn summary(&self) -> String {
    String::from("none")
  }
}

impl Summarizable for i32 {…}
```

- Second attempt, also wrong:

```
fn print_summary(s: &Summarizable) {
  print!("{}", s.summary());
}
```

  - There are lots of implementations of **`summary`**
  - Which one should be invoked?

What's Missing: Receiver Type

- This code was OK; why?

```
let x:i32 = 42;
x.summarize();
```

- The compiler knows which **`summarize`** to call, since it knows **`x:i32`**

Dynamic Dispatch

```
fn print_summary(s: &Summarizable) {
  print!("{}", s.summary());
}
```

- Object oriented languages, like Java, accept code like the above because they have dynamic dispatch
  - The correct method is determined at run time

- To implement dispatch in Rust, we use trait objects
- A trait object pairs data with runtime type information
  - Think: `(42, "I am an i32!")`

Trait Objects

- Use type **`dyn Summarizable`**, wrapped in a **`Box`**

```
fn print_summarizable(s: Box<dyn Summarizable>) {
    println!("{}", s.summary());
}
```

- Callers simply use **`Box`** to put the data on the heap

```
pub fn main() {
    let b = Box::new(42);
    print_summarizable(b);
}
```

Why the Box?

- Could we do this instead?

```
fn print_s(s: dyn Summarizable) {
  println!("{}", s.summary());
}
```

- Error!

```
17 | fn print_s(s: dyn Summarizable) {
   |            ^ doesn't have a size known at compile-time
   |
   = help: the trait `Sized` is not implemented for `(dyn
Summarizable + 'static)`
help: function arguments must have a statically known size,
borrowed types always have a known size
```

Lesson: **`dyn Summarizable`** has different sizes; **`Box<T>`** has one

Box and Size

- **`Box<i32>`** is a pointer to a heap-allocated **`i32`**
- **`Box<dyn Summarizable>`** is a fat pointer to a heap-allocated **`Summarizable`**
  - That is: (type information, pointer to data on the heap)

<u>Example</u>

```
struct Enormous { // 512 bytes (4 * 128)
  a: [i32; 128],
}

impl Summarizable for Enormous {…}

println!("{}", std::mem::size_of::<Enormous>());                  512
println!("{}", std::mem::size_of::<Box<Enormous>>());              8
println!("{}", std::mem::size_of::<Box<Summarizable>>());          Error
println!("{}", std::mem::size_of::<Box<dyn Summarizable>>());      16
```

Box: a Kind of Smart Pointer

- A smart pointer is a reference plus metadata, to provide additional capabilities
  - Originated in C++
  - Examples seen so far: `String`, `Vec<T>`, `Box<T>`
- Usually implemented as `struct`s
  - Which must implement the `Deref` and `Drop` traits
- New ones we will see: `Cell<T>`, `Rc<T>`, `Ref<T>`, …
- Check out *The Rustonomicon* for how to implement your own smart pointers!
  - https://doc.rust-lang.org/stable/nomicon/

Summary

- Use `Box<T>` to heap-allocate data, and reduce copying (via an ownership move)
  - Useful for non cyclic, immutable data structures
- Use trait objects, of type `Box<dyn Trait>`, to implement dynamic dispatch
  - For any trait type `Trait`
  - `Box` lets you use *fat pointers* for `dyn` trait objects, to provide runtime type information to enable dynamic dispatch
  - If you try to pass traits without `Box`, you may get errors about `Sized` because the compiler doesn't know how big things are

INTERIOR MUTABILITY

Rust Ownership and Mutation

- Recall Rust ownership rules
  - Each value in Rust has a variable that's called its *owner*; there can be only one
  - When the owner goes out of scope, the value will be dropped

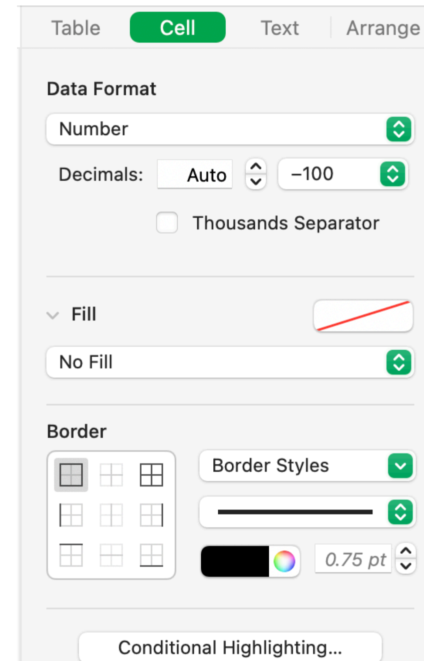
- Recall Rust mutability rules
  - Mutation can occur only through mutable variables (e.g., the owner) or references
  - Rust permits only one borrowed mutable reference (and no immutable ones at the same time)

But: Having both mutation and sharing is useful

- Example: a simple spreadsheet

```
struct CellStyle { fontSize: f64 }
struct Cell { style: CellStyle }
struct Table { cells: [Cell; 128] }
```

  - So: a **`Table`** *owns* its **`Cells`**



- But: a format inspector needs to read *and write* the cell data
  - Ensuring only one borrowed mutable reference would be awkward
  - Easier if the inspector has its own reference

Another Example

- Suppose you have a multiplayer chess game
  - Local data structures record the board state
  - Maybe the board is owned by the window that contains it

- What happens when a new move comes in from the network?
  - That's handled by a different software component, not the window

- Simplest design is to have multiple (mutable) references to the board
  - But Rust doesn't allow that

Relaxing Rust's Restrictions

- Architecturally, designating one owner that all accesses must go through can be awkward
  - We might end up wanting shared mutable access to the owner!

- Rust provides APIs by which you can get around the compiler-enforced restrictions against multiple mutable references
  - Use reference counting to manage lifetimes safely
  - Track borrows at run-time to overcome limited compiler analysis
  - Discipline is called interior mutability
  - But: extra checks at space and time overhead; some previous compile-time failures now occur at run-time

Multiple Pointers to a Value

- What's wrong with this code?

```
enum List {
  Nil,
  Cons(i32,Box<List>)
}
```

```
fn main() {
  let a = Cons(5,
    Box::new(Cons(10,
      Box::new(Nil))));
  let b = Cons(3, Box::new(a));
  let c = Cons(4, Box::new(a));//fails
}
```

  - `Box::new` takes ownership of its argument, so the second `Box::new(a)` call fails since `a` is no longer the owner
- How to allow something like this code?
  - Problem: Managing lifetime

Managing Lifetimes Dynamically

```
enum List {
  Nil,
  Cons(i32,Box<List>)
}
```

- Benefit of ownership: compiler knows when to free memory

```
{
  let nil_box = Box::new(List::Nil);
  // free memory HERE (nil_box is going out of scope)
}
```

- Suppose **Box** *didn't* own its data:

```
let nil_box = Box::new(List::Nil);
let one_list = List::Cons(1, nil_box);
{
    let two_list = List::Cons(2, nil_box);
    // two_list is going out of scope; free nil_box too?
}
```

```
error[E0382]: use of
moved value: `nil_box`
```

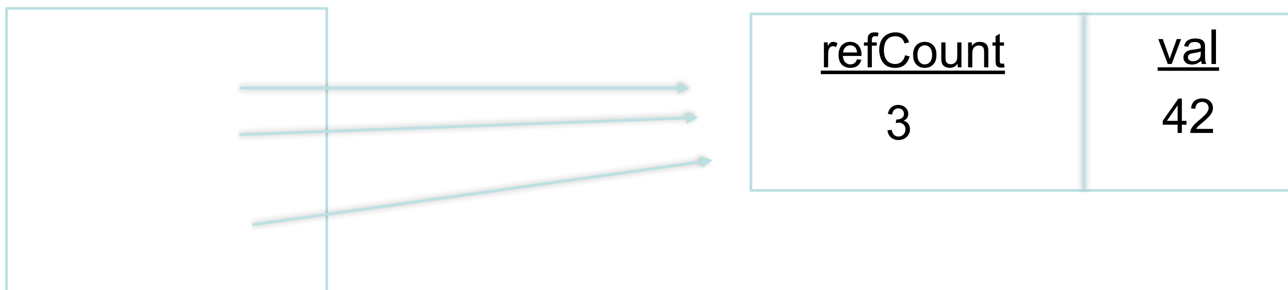
- (**Box** does own its data so the above pattern is not allowed.)

Rc<T>: Multiple Owners, Dynamically

- This is a *smart pointer* that associates a counter with the underlying reference
- Calling **clone** copies the pointer, not the pointed-to data, and bumps the counter by one
  - By convention, call **`Rc::clone(&a)`** rather than **`a.clone()`**, as a visual marker for future performance debugging
    - In general, calls to **`x.clone()`** are possible issues
- Calling **drop** reduces the counter by one
- When the counter hits zero, the data is **freed**

Rc::clone "Shares" Ownership

- **`Rc`** associates a refCount with the value



stack (for example)

heap

- `let x = Rc::new(42);`
- `let y = Rc::clone(x);`
- `let z = Rc::clone(x);`

does heap allocation, like Box::new, but uses reference counting

clone() increments reference count

clone() increments reference count

Lists with Sharing

```
enum List {
  Nil,
  Cons(i32,Rc<List>)
}

use List::{Cons, Nil};

fn main() {
  let a = Rc::new(Cons(5,
    Rc::new(Cons(10,
      Rc::new(Nil)))));
  let b = Cons(3, Rc::clone(&a));
  let c = Cons(4, Rc::clone(&a));//ok
}
```

Nb. `Rc::strong_count` returns the current ref count

Reference Counting: Summary

- To *create*: `let r = Rc::new(...);`
- To *copy* a pointer: `let s = Rc::clone(&r);`
  - Increments the reference count
- To *move* a reference: `let t = s;`
  - Does *not* increment reference count; `s` no longer the owner
- To *free* is automatic: `drop` is called when variables go out of scope, reducing the count; freed when 0

- See docs:
  - https://doc.rust-lang.org/book/ch15-04-rc.html
  - https://doc.rust-lang.org/std/rc/index.html

Quiz 1

```
fn print_refcount(r: Rc<i32>) {
    println!("{}", Rc::strong_count(&r));
}

fn main() {
    let forty_two = Rc::new(42);
    print_refcount(forty_two);
    {
        let v = Rc::clone(&forty_two);
        print_refcount(v); // What does this print?
    }
}
```

A. 0
B. 1
C. 2
D. This code doesn't compile

Quiz 1

```
fn print_refcount(r: Rc<i32>) {
    println!("{}", Rc::strong_count(&r));
}

fn main() {
    let forty_two = Rc::new(42);
    print_refcount(forty_two);
    {
        let v = Rc::clone(&forty_two);
        print_refcount(v); // What does this print?
```

```
error[E0382]: borrow of moved value: `forty_two`
  --> src/main.rs:11:27
   |
8  |     let forty_two = Rc::new(42);
   |         --------- move occurs because `forty_two` has type `Rc<i32>`, which does not
implement the `Copy` trait
9  |     print_refcount(forty_two);
   |                    --------- value moved here
10 |     {
11 |         let v = Rc::clone(&forty_two);
   |                           ^^^^^^^^^^ value borrowed here after move
```

Quiz 2

```
fn print_refcount(r: &Rc<i32>) {
    println!("{}", Rc::strong_count(r));
}

fn main() {
    let forty_two = Rc::new(42);
    {
        let v = Rc::clone(&forty_two);
    }
    print_refcount(&forty_two); // What does this print?
}
```

A. 0
B. 1
C. 2
D. This code doesn't compile

Quiz 2

```
fn print_refcount(r: &Rc<i32>) {
    println!("{}", Rc::strong_count(r));
}

fn main() {
    let forty_two = Rc::new(42);
    {
        let v = Rc::clone(&forty_two);
    }
    print_refcount(&forty_two); // What does this print?
}
```

A. 0
B. 1 `v` went out of scope, so the reference count is 1 (once again).
C. 2
D. This code doesn't compile

Risks of Reference Counts

- Cyclic data is problematic
  – Suppose the arrows are `Rc` references

  – Reference counts are always positive; will never be deallocated!

- Can fix by using *weak references* (see docs)
  - App must be prepared for referent to be revoked
  - These are not required for the assignment

Rc References: Mutation?

- Attempt 1:

```
let mut b = Rc::new(42);
*b = 43;
```

```
warning: variable does not need to be mutable
 --> src/main.rs:4:9
  |
4 |     let mut b = Rc::new(42);
  |         ----^
  |         |
  |         help: remove this `mut`
  |
  = note: `#[warn(unused_mut)]` on by default

error[E0594]: cannot assign to data in an `Rc`
 --> src/main.rs:5:5
  |
5 |     *b = 43;
  |     ^^^^^^^ cannot assign
  |
  = help: trait `DerefMut` is required to modify through a dereference,
but it is not implemented for `Rc<i32>`
```

Rc References: No Mutation!

```
error[E0594]: cannot assign to data in an `Rc`
 --> src/main.rs:5:5
  |
5 |     *b = 43;
  |     ^^^^^^^ cannot assign
  |
  = help: trait `DerefMut` is required to modify through a dereference, but it is not implemented for
`Rc<i32>`
```

`Rc` only allows *immutable* contents

```
let mut b = Rc::new(42);
b = Rc::new(43); // fresh heap alloc
```

`mut b` means that I can reassign **`b`**, but not the object it references!

But: Cells are Mutable

- `Cell<T>`: like `Box<T>` but with mutable contents

  `pub fn set(&self, val: T)`
  - *moves* the data in

  `pub fn get(&self) -> T`
  - *copies* the data out

  `pub fn take(&self) -> T`
  - *moves* the data out, leaving `Default::default()`

  `pub fn get_mut(&mut self) -> &mut T`
  - requires a `&mut self`

Cell example (from Rust book)

```rust
use std::cell::Cell;

struct SomeStruct {
    regular_field: u8,
    special_field: Cell<u8>,
}

let my_struct = SomeStruct {
    regular_field: 0,
    special_field: Cell::new(1),
};

let new_value = 100;

// ERROR: `my_struct` is immutable
// my_struct.regular_field = new_value;

// WORKS: although `my_struct` is immutable, `special_field` is a `Cell`,
// which can always be mutated
my_struct.special_field.set(new_value);
assert_eq!(my_struct.special_field.get(), new_value);
```

Cell Limitations

- `Cell` is great if
  - you can copy the contents in and out
  - and you have mutable references to the cell whenever you want to modify the cell's contents
  - and you can reason statically about lifetimes
- But what if you can't or don't?
  - e.g., you want to access contents of cell without copying it out (maybe it's a struct that's not `Copy`)
- Enter: `RefCell`

RefCell<T>

`pub const fn new(value: T) -> RefCell<T>`

- Looks similar…

`pub fn borrow(&self) -> Ref<'_, T>`

- This is a *dynamic* borrow
- *"The borrow lasts until the returned* **`Ref`** *exits scope. Multiple immutable borrows can be taken out at the same time…Panics if the value is currently mutably borrowed. "*

`pub fn borrow_mut(&self) -> RefMut<'_, T>`

- Note **`&self,`** not **`&mut self`**!
- *"The borrow lasts until the returned* **`RefMut`** *or all* **`RefMuts`** *derived from it exit scope. The value cannot be borrowed while this borrow is active."*

`Ref` and **`RefMut`** are *only* for use with **`RefCell`**

Ref<T> vs. &T

- Both **`Ref<T>`**, returned by **`borrow*`**, and **`&T`**, implement **`Deref`**
  - Code that uses them will be similar

`&T`

```
let x = 42;
let r = &x;
assert_eq!(*r, 42);
```

`Ref<T>`

```
let cell = RefCell::new(42);
let cell_ref : Ref<i32> = cell.borrow();
assert_eq!(*cell_ref, 42);
```

Static vs. Dynamic Borrow Tracking

- `&T` an d `&mut T`: *static* (compile-time) tracked of borrows

- `RefCell<T>::borrow*`: *dynamic* (run-time) tracked of borrows

```
pub fn borrow(&self) -> Ref<'_, T>
pub fn borrow_mut(&self) -> RefMut<'_, T>
```

  - `Ref<'_, T>`, `RefMut<'_, T>` implement dynamic tracking of outstanding, borrowed references
  - If `borrow_mut()` with an outstanding `Ref`, panic!

- Static tracking is better if you can make it work
  - no run time overhead; earlier bug detection

How Does Dynamic Borrowing Work?

- Each `RefCell` has a *borrow count* to track outstanding `Ref`s and `RefMut`s for that `RefCell`
  - `RefCell` `borrow` and `borrow_mut` increment the count
  - When a `Ref` (or `RefMut`) goes out of scope, Rust calls `drop()`, which decrements the borrow count

```
use std::cell::RefCell;
let c = RefCell::new(5); // imm_count=0
let m = c.borrow();      // imm_count=1
let b = c.borrow_mut();  // panic!
```

Shared Mutable Data

- **Use `Rc<RefCell<T>>`**
  - The `RefCell` permits mutating `T` (at risk of run-time borrow errors)
  - `Rc` permits sharing, e.g., within a data structure
- `Rc<RefCell<u32>>` has *two* counts:
  - Reference count for `Rc` (should this `RefCell` be deallocated?)
    - Incremented via `Rc::clone()`
    - Dynamic version of lifetime
  - Borrow count for `RefCell` (are `borrow(), borrow_mut()` safe?)
    - Incremented via `RefCell` `borrow` and `borrow_mut`
    - Dynamic version of borrow checking

Quiz 3

```
let r1 = Rc::new(RefCell::new(42));
let r2 = r1.clone();
let m = (*r1).borrow_mut();
*m = 43;
println!("{:?}", *r2.borrow());
```

```
A. "42"
B. "43"
C. panic
D. Compiler error
```

Quiz 3

```
let r1 = Rc::new(RefCell::new(42));
let r2 = r1.clone();
let m = (*r1).borrow_mut();
*m = 43;
println!("{:?}", *r2.borrow());
```

A. "42"

B. "43"

C. panic

D. Compiler error

```
error[E0596]: cannot borrow `m` as mutable, as it is not declared as mutable
  --> src/main.rs:10:10
   |
9  |         let m = (*r1).borrow_mut();
   |             - help: consider changing this to be mutable: `mut m`
10 |         *m = 43;
   |          ^ cannot borrow as mutable
```

Quiz 3

```
let r1 = Rc::new(RefCell::new(42));
let r2 = r1.clone();
let m = (*r1).borrow_mut();
*m = 43;
println!("{:?}", *r2.borrow());
```

`borrow_mut()` returns a `DerefMut`

```
DerefMut:
  pub fn deref_mut(&mut self) -> &mut Self::Target
```

To mutate the referenced value, we need a *mutable* `DerefMut`

Quiz 4

```
let r1 = Rc::new(RefCell::new(42));
let r2 = r1.clone();
let mut m = (*r1).borrow_mut();
*m = 43;
println!("{:?}", *r2.borrow());
```

A. "42"

B. "43"

C. panic

D. Compiler error

Quiz 4

```
let r1 = Rc::new(RefCell::new(42));
let r2 = r1.clone();
let mut m = (*r1).borrow_mut();
*m = 43;
println!("{:?}", *r2.borrow());
```

A. "42"

B. "43"

C. panic

D. Compiler error

`m`'s mutable borrow of the `RefCell` is still outstanding when `borrow()` is invoked.

Quiz 5

```
let r1 = Rc::new(RefCell::new(42));
let r2 = r1.clone();
{
    let mut m = (*r1).borrow_mut();
    *m = 43;
}
println!("{:?}", *r2.borrow());
```

A. "42"

B. "43"

C. panic

Quiz 5

```
let r1 = Rc::new(RefCell::new(42));
let r2 = r1.clone();
{
    let mut m = (*r1).borrow_mut();
    *m = 43;
}
println!("{:?}", *r2.borrow());
```

```
A. "42"
B. "43"
C. panic
```

Summary

- From the book [1]:
  - `Rc<T>` enables multiple owners of the same data; `Box<T>` and `RefCell<T>` have single owners.
  - `Box<T>` allows immutable or mutable borrows checked at compile time; `Rc<T>` allows only immutable borrows checked at compile time; `RefCell<T>` allows immutable or mutable borrows checked at runtime.
  - Because `RefCell<T>` allows mutable borrows checked at runtime, you can mutate the value inside the `RefCell<T>` even when the `RefCell<T>` is immutable.

[1] https://doc.rust-lang.org/book/ch15-05-interior-mutability.html
Additional examples: https://doc.rust-lang.org/rust-by-example/std/rc.html

A Quick Summary

- **`&mut`**: use when you only need one mutable reference
- **`Rc`**: reference-counted, shared reference to the heap
- **`RefCell`**/**`Cell`**: mutable contents *even when immutable*
  - Borrowing via a special **`Ref`** value, which ensures that Rust's borrow checking rules are followed *dynamically*
  - Combine with **`Rc`** for shared mutability
- **`Ref`**/**`RefMut`**: only used for accessing **`RefCell`**.

Conclusions

- Ideally, design Rust programs so each value has one owner
  - But that's not always possible
  - Even when it is, those designs may have other costs

- When necessary, use **`Rc`**, **`RefCell`** to relax Rust's static constraints
  - Part of a programming discipline called interior mutability.
  - With great power comes great responsibility!