CMSC 330: Organization of Programming Languages

Reference Counting

and 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)

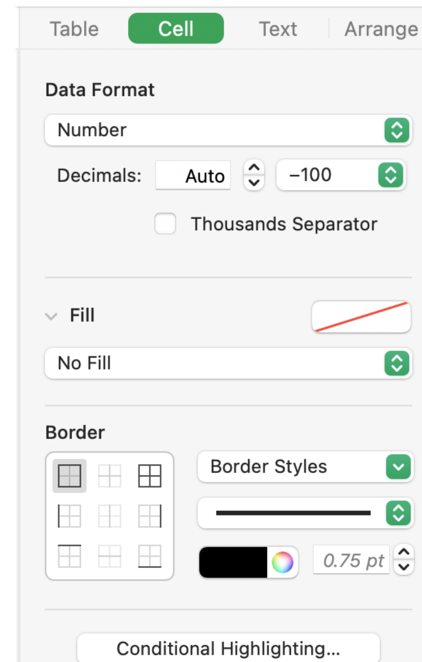
But: Mutation and Sharing is Useful

- 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
  - Also a pain to program: Experimental **GcRef** to ease this

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`

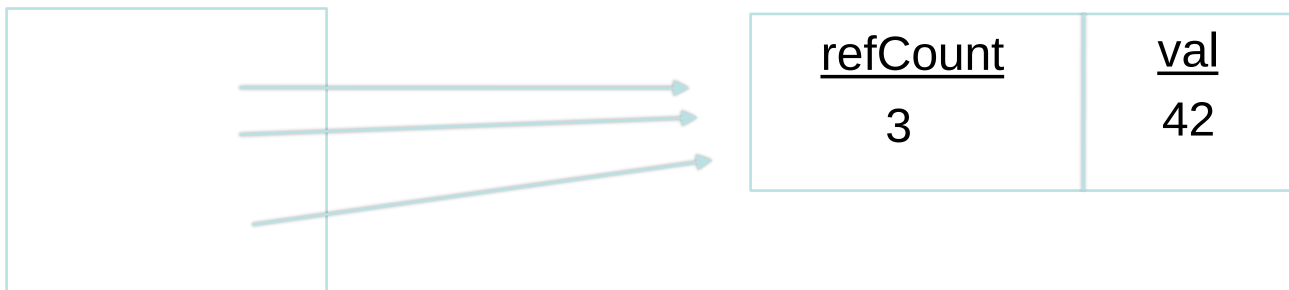
- (**Box** does own its data so the above pattern is not allowed.)

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?
    }
}
```

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

```
error[E0382]: borrow of moved value: `forty_two`
  --> src/main.rs:46:27
   |
43 |     let forty_two = Rc::new(42);
   |         --------- move occurs because
`forty_two` has type `std::rc::Rc<i32>`, which
does not implement the `Copy` trait
```

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

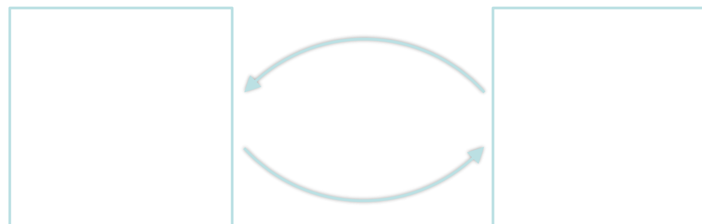
```
fn print_refcount(r: &Rc<i32>) {
    println!("{}", Rc::strong_count(r));
}

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
C. 2
D. This code doesn't compile

`v` went out of scope, so the reference count is 1 (once again).

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 project 5

Rc References: Mutation?

- With **`Rc`** I can now make multiple references and safely manage lifetimes. Great! Let's see if I can mutate the reference's contents

```
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!

Digression: 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)

```
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

- Back to the beginning: We were looking for a way to have *shared, mutable* data. How do we do it? **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
- Note: `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.

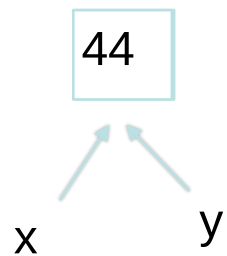
[1] https://doc.rust-lang.org/book/ch15-05-interior-mutability.html
Additional examples: https://doc.rust-lang.org/rust-by-example/std/rc.html

Garbage collection

- Assuming you need shared, mutable references, could use **`Rc`**:
  - + Free memory ASAP
  - - Have to store reference count
  - - Have to manually increment count with clone()
  - - Manual cycle management
  - +/- Manage mutability yourself
- **Garbage collection** (like Java):
  - - Free memory later (when?)
  - + Everything is automatic (almost…), easier to program
  - - Memory and performance cost

Example

```
let mut x = GcRef::new(42);
let mut y = x;
*x = 43;
*y = 44;
```



GcRef<T> and Mutability

- Can always make a **`GcRef`** that allows mutation
- Like "automatic" interior mutability

```
#[derive(Trace, Finalize)]
pub struct IntContainer {
    n: i32,
}

pub fn test() {

    let c1 = GcRef::new(IntContainer{n: 42});
        c1.n = 47; // ERROR: c1 is immutable. BUT...

    let mut c2 = c1; // GcRef is Copy, so this makes an alias
    c2.n = 47; // Allowed because c2 is mut
    assert_eq!(c1.n, 47); // passes!
}
```

GcRef Versatility

- Can use **`GcRef`** even if you don't need mutability
- Can use **`GcRef`** even if you don't need multiple references
- Performance, memory cost are low (but present)
- **`GcRef<T>`** can replace:
    - **`Rc<RefCell<T>>`**
    - **`Rc<T>`**
- Note that **GcRef** is experimental

GcRef documentation: https://crates.io/crates/bronze_gc

GC considerations (1)

- Garbage collection requires *tracing* to find live objects

```
#[derive(Trace, Finalize)]
pub struct Foo { ... }
```

- No dynamic ownership checks. This allows "surprise" mutation

Rust references

```
let mut x = Foo::new();
// suppose x satisfies property P now

let mut y = Bar::new(x);
y.baz();
x.foo(); // error: x was moved
```

GcRef

```
let mut x = GcRef::new(Foo::new());
// suppose x satisfies property P now

let mut y = GcRef::new(Bar::new(x));
y.baz();
x.foo();
// x may no longer satisfy P
// because baz() mutated it!
```

GC considerations (2)

- Less verbose (avoid **`clone()`**, **`Rc<RefCell<T>>`**)
- Don't have to worry about cycles
- As with **RefCell**, we violate the "only one mutable reference at a time" rule
- Is it a good idea? We hope you'll tell us.

Back to the Beginning: Shared Table, Two Ways

```
struct CellStyle { fontSize: f64 }
struct Cell { style: CellStyle }
struct Table {cells: [Cell; 1]}


struct Document {
   table: Rc<RefCell<Table>>,
}

struct Inspector {
   table:  Rc<RefCell<Table>>,
}

fn main() {
   let table = Rc::new(
     RefCell::new(Table::new()));
   let inspector = Inspector {
      table: table.clone()};
   let document = Document {
       table: table.clone()};
   table.borrow().foo();
}
```

Rust with Rc/RefCell

```
struct CellStyle { fontSize: f64 }
struct Cell { style: CellStyle }
struct Table {cells: [Cell; 1]}

struct Document {
   table: GcRef<Table>,
}

struct Inspector {
   table:  GcRef<Table>,
}

fn main() {
   let table = GcRef::new(
     Table::new());
   let inspector = Inspector {
      table: table};
   let document = Document {
       table: table};
      table.foo();
   ...
}
```

Rust with GcRef

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`**.
- **`GcRef`**: garbage-collected references to mutable heap locations
  - Can only mutate through **`mut GcRef`**, but can always copy a **`GcRef`** to get a **`mut GcRef`**

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`**, and **`GcRef`** to relax Rust's static constraints
  - Part of a programming discipline called interior mutability.
  - With great power comes great responsibility!