Type State

CS242

Lecture 10

APIs

Consider a typical use of a file API:

```
File f = open("MyFile");
Char c = f.read();
f.close()
```

APIs

File operations mutate state and can change what operations are legal

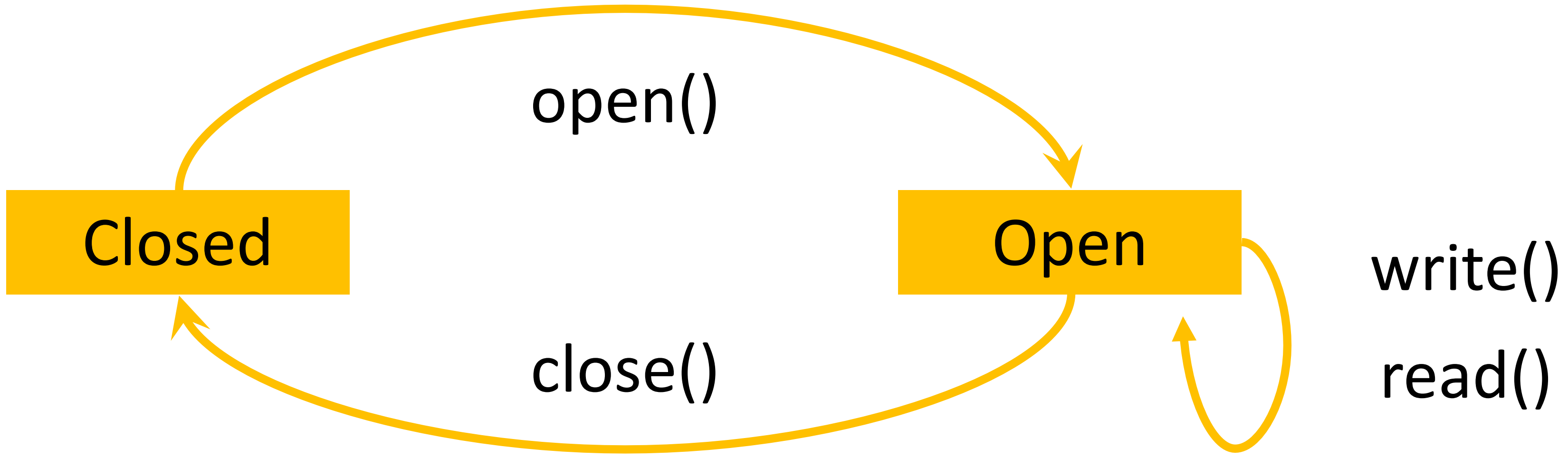
```
File f = open("MyFile");    // opening the file enables reading
Char c = f.read();
f.close()                   // but once the file is closed, reading is no
                            // legal even though f is still available
```

Stateful APIs

- Many APIs are stateful in this way
- Correct usage depends on the state of the system
  - Which changes over time as API calls are made
- States and state changes are commonly modeled using finite state machines

Files

- Files can be open or closed
- A closed file can only be opened
- An open file can be read, written or closed



Discussion

- Many similar examples of this two state machine in real APIs:

- File open/close
- Lock acquire/release
- Message encrypted/decrypted
- User logged in/logged out
- Resource initialized/unitialized

More Complex Machines

- File example can be refined, revealing more states specific to reading/writing

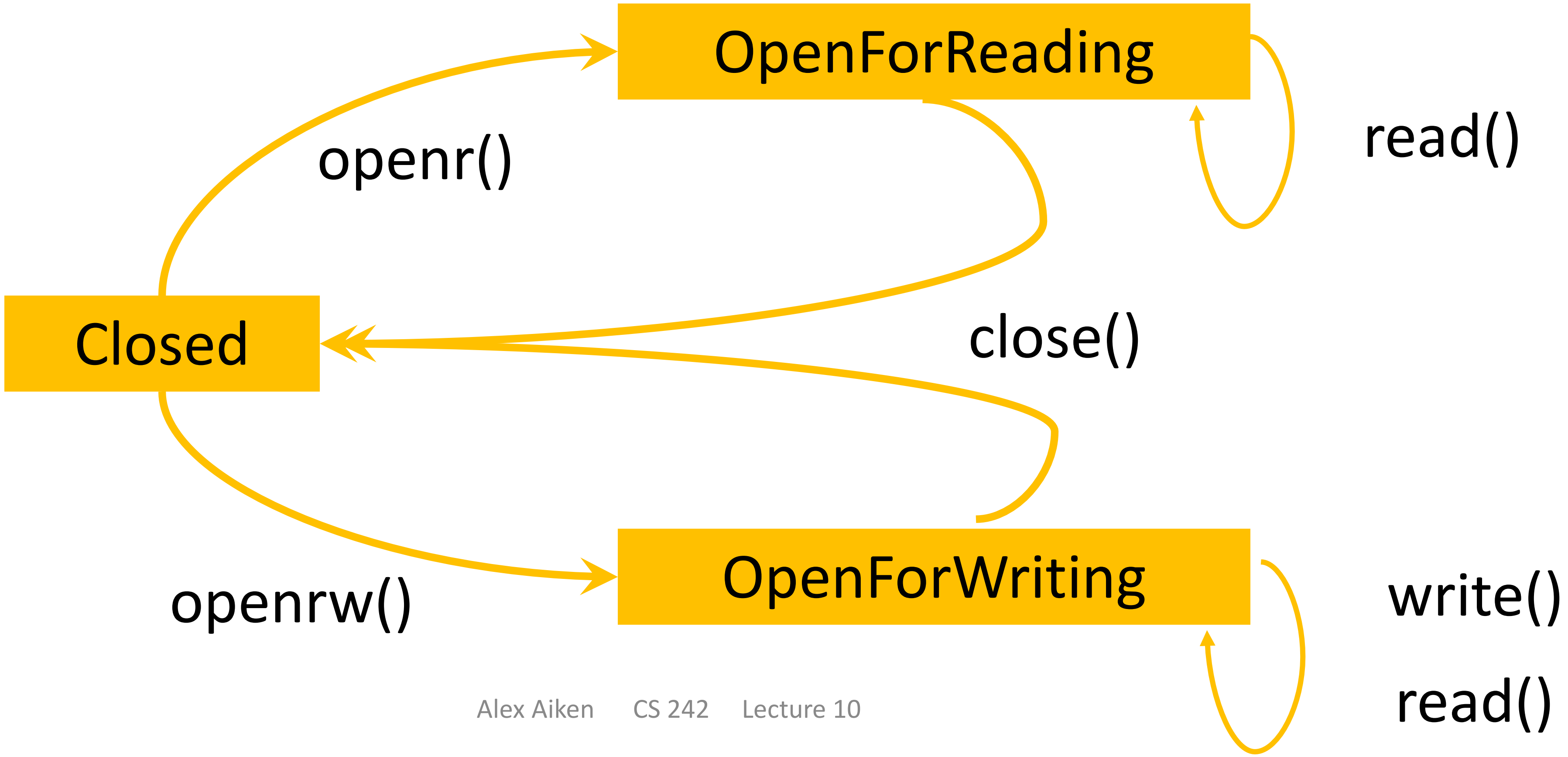
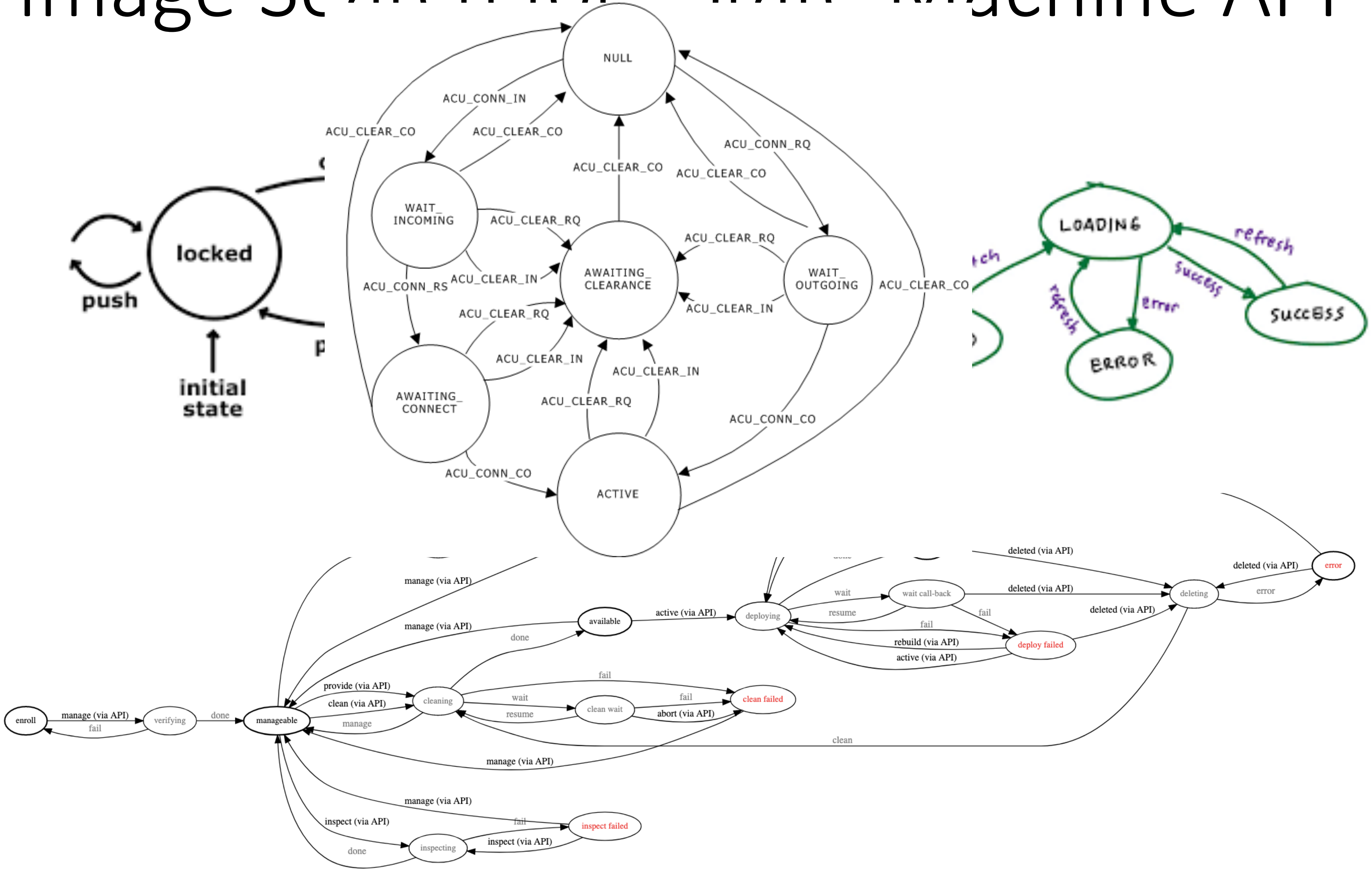


Image Search for "State Machine API"



Enforcing APIs

- We would like to enforce that API usage is correct according to a state machine specification

- Guarantees
  - We start in a correct state
  - The only calls that are made are valid in the current state
  - Can also enforce that we end in a correct state
    - e.g., Don’t leave a resource locked forever

Type State

- Idea: Use the type system

- Each state machine state corresponds to a distinct type

- Method invocations cause transitions in the state diagram
  - open(): ClosedFile -> OpenFile
  - close(): OpenFile -> ClosedFile
  - read(): OpenFile -> OpenFile

A Possible Implementation

```
Class  FileRecord {
    File f;
    Str name;  }

Class OpenFile {
        FileRecord r;
        new OpenFile(name: Str);
        read(): Char;
        close(): ClosedFile }

Class ClosedFile {
        FileRecord r;
        new ClosedFile(r: FileRecord);
        open(): OpenFile;  }
```

Example

```
f = new OpenFile("foo")        // f is of type OpenFile
c = f.read()
x = f.close()                  // x is of type ClosedFile

//  but ...
d = f.read()    // f has been closed!
```

Discussion

- The OpenFile and ClosedFile types allow us to express the transition from an open file to a closed file in the type system
  - And even back again

- The types only permit valid operations for the state of the file

- But ...
  - Nothing gets rid of the OpenFile objects when the file is closed
  - We could null out the FileRecord, but the OpenFile object would still exist

What Do We Want?

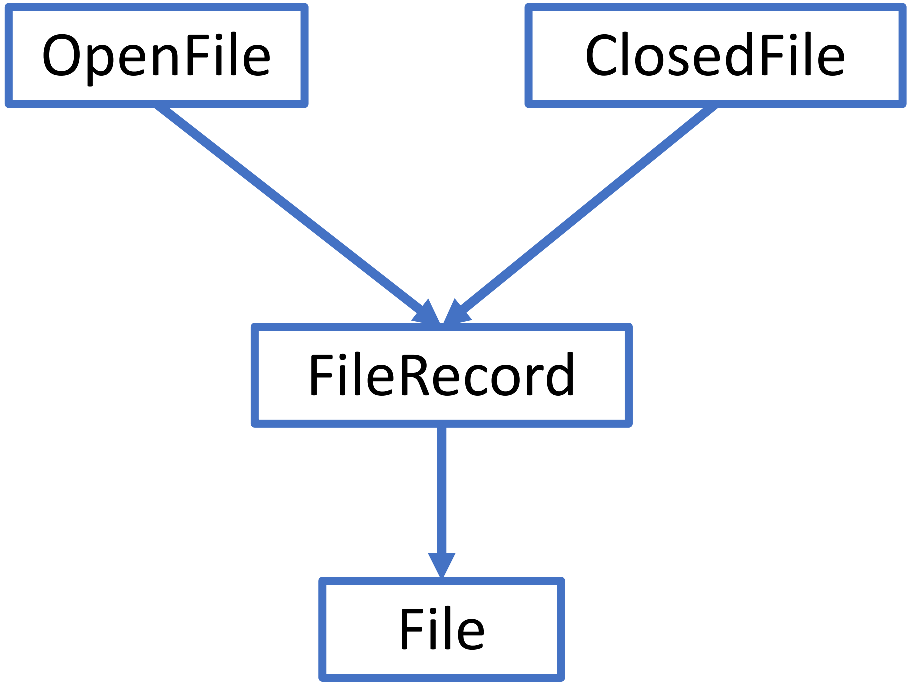
```
f = new OpenFile("foo")
c = f.read()
x = f.close()
// ideally at this point the f object would be deallocated
// and it would also be impossible to invoke operations on f
// So...
d = f.read()    // this should be a type error!
```

The Real Problem

- Types are not the problem
  - We can express the state transitions as functions that map one type to another
- Keeping track of object references is the problem
  - In particular, tracking *aliasing* between names

Aliasing

- OpenFile and ClosedFile methods both modify the state of the File object in the FileRecord
- An example of *aliasing*
  - Having multiple names (ways to access) the same value
- Either object can change the state of the file without the knowledge of the other



Aliasing Control

A Classic Example

```
copy(char *x, char  *y) {
      ...
}
```

But what about copy(a,a)?

A Classic Example

```
copy(restrict char *x, restrict char  *y) {
      ...
}
```

Semantics: In C, a restricted pointer cannot be aliased to any other pointer in scope.

A Point of View

- Aliasing is bad

- State can be modified through one name and those changes are visible through a different name
  - Leads to subtle and difficult bugs

- But aliasing is very common in real programs
  - Impossible to avoid
  - E.g., references passed as arguments to functions
  - Object-oriented code is particularly prone to generating aliasing

Idea #1

- Maybe aliasing is not the problem ...

- Problems arise only when aliasing is combined with mutation

- So, disallow mutation!
  - The pure functional programming viewpoint

Could This Really Work?

- People have studied pure functional languages for decades
  - No mutation, whenever a data structure is changed a copy is made
- A surprising number of standard algorithms are just as efficient without mutation of state
  - Sometimes just amortized bounds, but that is still quite good!
- But there are some operations that seem to fundamentally require mutation to be efficient
  - Update in place of an array is O(1)
  - The best known functional update is O(log N) in the size of the array

A Practical Approach

- Split the world into mutable and immutable values

- Rust
  - let x = 5   // immutable
  - let mut x = 5   //mutable
  - x = 3   // only allowed if x is mutable

- ML
  - let x = 5   // immutable
  - let x = ref 5   // mutable
  - x := 3

Separating Mutable & Immutable

- Not entirely a new idea
  - E.g., const in C
- Gaining in popularity
  - More languages are making this distinction
  - With immutability being the default
- Now accepted as a good idea
  - Limit the possibility of mutation to places it is really needed
  - Make these points obvious in the syntax & types

Idea #2

- Control aliasing in the type system
  - Track it, restrict it, or even disallow it

- Ownership types
  - Track aliases using types

- There is a large literature on ownership types
  - Some quite elaborate ...

Ownership in Rust

- Rust has a simple ownership model
- There is always a single *owner* variable of every object
  - Owning = responsible for the resources of the object
- Implications
  - An object with no owner is deallocated
    - When an owner goes out of scope, the owned object is deallocated
  - Copies transfer ownership
    - x = y removes ownership from y and transfers it to x
    - y can no longer be used after the assignment

Ownership Example

```
fn main(){
    let v = vec[1,2,3];     // v owns the vector
    let v2 = v;             // moves ownership to v2
    // let v3 = v[1]  compile-time error!
    display(v2);            // ownership is moved to display
    // println(v2);  compile-time error!
}

fn display(v:Vec<i32>){
     println(v);
     // v goes out of scope here and the vector is deallocated
}
```

Another Ownership Example

```
A() {
X = new Foo();   // X is the owner
Y = Bar(X)       // ownership is transferred to the argument of Bar
                 //  and then back to Y
//  Y goes out of scope and the vector is deallocated
}


Bar(Z) {
   return Z     // ownership is transferred back to the caller
}
```

Lifetimes

- Rust reasons about aliasing/ownership by using *lifetimes*

- The lifetime of a variable is the span between
  - The definition (first use)
  - The last use

- Roughly: Lifetimes of aliases cannot overlap
  - Thus it is important to minimize lifetimes
  - We will refine this rule shortly

Lifetimes

```
fn main(){
    let v = vec[1,2,3];     // vector v owns the object
    let v2 = v;             // moves ownership to v2
    // let v3 = v[1]  compile-time error!
    display(v2);            // ownership is moved to display
    // println(v2);  compile-time error!
}

fn display(v:Vec<i32>){
    println(v);
    // v goes out of scope here and the vector is deallocated
}
```

Lifetimes: A Compile Time Error

```
fn main(){
  let v = vec[1,2,3];    // vector v owns the object
  let v2 = v;            // moves ownership to v2
  let v3 = v[1]          // compile-time error!
  display(v2);           // ownership is moved to display
  // println(v2);  compile-time error!
}

fn display(v:Vec<i32>){
    println(v);
    // v goes out of scope here and the vector is deallocated
}
```

Lifetimes: A Fix

```
fn main(){
  let v = vec[1,2,3];     // vector v owns the object 2
  let v3 = v[1]           // now this works …
  let v2 = v;             // moves ownership to v2
  display(v2);            // ownership is moved to display
  // println(v2);  compile-time error!
}

fn display(v:Vec<i32>){
    println(v);
    // v goes out of scope here and the vector is deallocated
}
```

Aliasing Control in Rust

- Having only a single owner is painful in many situations
  - Can never have another name for an object or even a piece of an object
  - E.g., makes it impossible to name a subarray
  - And we often don't need to take ownership anyway

- Rust allows the creation of explicit aliases
  - called *references* or *borrows*

- There are two kinds of references:
  - mutable
  - immutable

Example: Immutable Reference

```
A() {
X = new Foo();   // X is the owner
Y = &X           // An immutable reference to X;  X is still the owner.
Bar(Y)           // pass an immutable reference to Bar
}


Bar(&Z) {
   ... =  .. Z ...          // can read from Z in Bar as many times as we like
   //    Global.x = Z       but if we try to store Z somewhere that outlives Bar we get an error
}
```

Example: Immutable Reference

```
A() {
X = new Foo();   // X is the owner
Y = &X                // An immutable reference to X;  X is still the owner.
Bar(Y, Y)              // pass two immutable references to Bar
}


Bar(&A, &B) {
   ... =  .. A ... // can read from A and B in Bar as many times as we like
   ... = ... B ...

}
```

Example: Mutable Reference

```
A() {
X = new Foo();      // X is the owner
Y = &mut X;         //  Y is a mutable reference to X
Bar(Y)              // pass a mutable reference to Bar
}


Bar(&mut Z) {
   Z.f =  ... // can mutate Z
}
```

Example: Mutable Reference

```
A() {
X = new Foo();      // X is the owner
Y = &mut X;         //  Y is a mutable reference to X
Bar(Y, Y)           // Error: Cannot have two mutable references to X
}


Bar(&mut A, &mut B) {   // since A and B are mutable, they cannot alias
  A.f =  ... // can mutate A
  B.f = ...  // can mutate B
}
```

Reference Rules

- A reference cannot outlive its referent
  - No dangling references ...
- A mutable reference cannot be aliased
- Meaning:
  - There can be one mutable reference to an object in scope
  - There can be any number of immutable references
  - The owner’s lifetime must contain the lifetime of all references

Example: Immutable Reference

```
A() {
X = new Foo();   // X is the owner
Y = &X           // An immutable reference to X;  X is still the owner.
Bar(Y)           // pass an immutable reference to Bar; the reference's lifetime is the lifetime of Bar
}


Bar(&Z) {
  ... =  .. Z ...          // can read from Z in Bar as many times as we like
  //    Global.x = Z       but if we try to store Z somewhere that outlives Bar we'll get an error
}
```

Back to Type State

- Recall type state allowed us to express state changes in the type system:

```
// f: OpenFile
x = f.close() // x is of type ClosedFile
```

- Ownership types can be used to make objects corresponding to the previous API state inaccessible

The Type State Example

```
f = new OpenFile("foo")     //  f is the owner
c = f.read()
x = f.close()   // x is of type ClosedFile, transfers file ownership f -> x


//  then ...
d = f.read()    // generates a type error: f is not the owner
```

Type State Abstraction

- Objects of a given state support only the methods available in that state

- Methods that change the internal API state
  - Return a new object of the appropriate type
  - Transfer ownership to the new object so that the references to the previous state become inaccessible

- Thus only objects of the correct type are ever accessible by the program

Discussion

- Ownership rules are very restrictive
  - Program must be *linear* in owned objects
  - Exactly one owner at all times
  - Implies no copies can be made

- Three techniques help:
  - Using immutable data wherever possible
  - Deep copies are OK (*cloning*)
  - Borrowing creates a reference that can be used
    - Does not transfer ownership
    - Implies a borrowed reference cannot deallocate an object
    - The owner cannot deallocate an object until all borrowed references are returned
    - Borrowed references have a different syntax and type

Ownership in Practice

- Ownership has been studied for > 20 years

- Rust is the first full language to support ownership types
  - The major new feature

- Experience is that Rust's ownership system helps
  - Enables manually managed memory without the bugs
  - Makes it possible to write efficient and correct code
  - Ownership types are the key
  - Which is not to say ownership is always easy to use ... it's not!