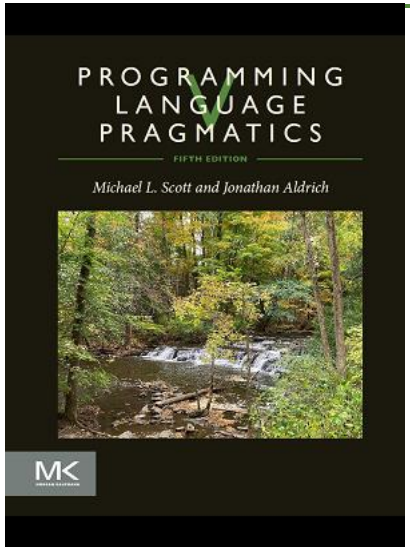
Ownership in Rust

This material is based heavily on the Rust book, as adapted by Will Crichton et al.



Programming Language Pragmatics, Fifth Edition

Michael L. Scott and Jonathan Aldrich

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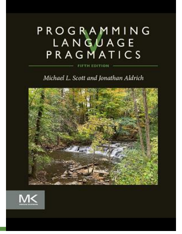
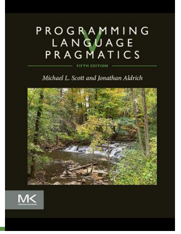
Limitations of garbage collection



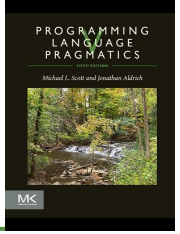
- Garbage collection (GC) provides safe, convenient memory management
  - Ideal for applications programming
- But GC can be limiting for systems programming
  - May not be willing to pay GC’s time and space costs
  - May need control of memory layout and use
  - GC failure modes can be problematic
    - Under GC, servers slow down when running out of memory
    - Crashing with “out of memory” may be better—can just restart the server
- Manual memory allocation may be needed in these conditions
  - But in most languages, this sacrifices safety

Rust provides safe manual memory management



- Rust is a systems-oriented programming language
  - manual memory management
  - concurrency and parallelism
- Rust's *ownership type system* ensures safety
  - from memory leaks and dangling references (today)
  - from data races in concurrent programs (later)

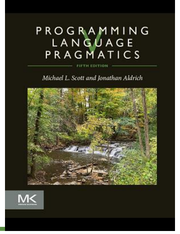
Safety in Rust



- Safety in Rust means a lack of undefined behavior
- Example of undefined behavior (from the Rust book):

```
fn read(y: bool) {
    if y {
        println!("y is true!");
    }
}

fn main() {
    read(x); // oh no! x isn't defined!
    let x = true;
}
```

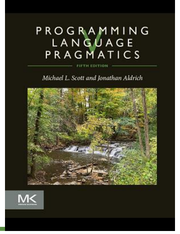
- It is undefined behavior to read a variable before it is defined
- Why is undefined behavior bad?
  - Well, it might execute just fine
  - But the program above could read garbage data, making results unpredictable
  - In general, undefined behavior can cause crashes or security vulnerabilities



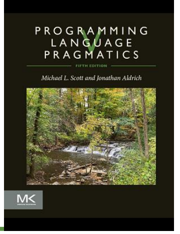
How Rust ensures safety

- Key goal of Rust: ensure program don't have undefined behavior
  - Combination of static and dynamic checks
  - Check as much as possible statically
- Bugs are still possible! But certain kinds of bugs can't happen.
- Ownership in Rust is a discipline for using memory
- Ownership prevents undefined behavior related to memory (except in *unsafe* code)
  - Reading uninitialized memory
  - Using memory after it is freed
  - Freeing memory twice
  - Memory leaks (forgetting to free memory)

Ownership in Rust

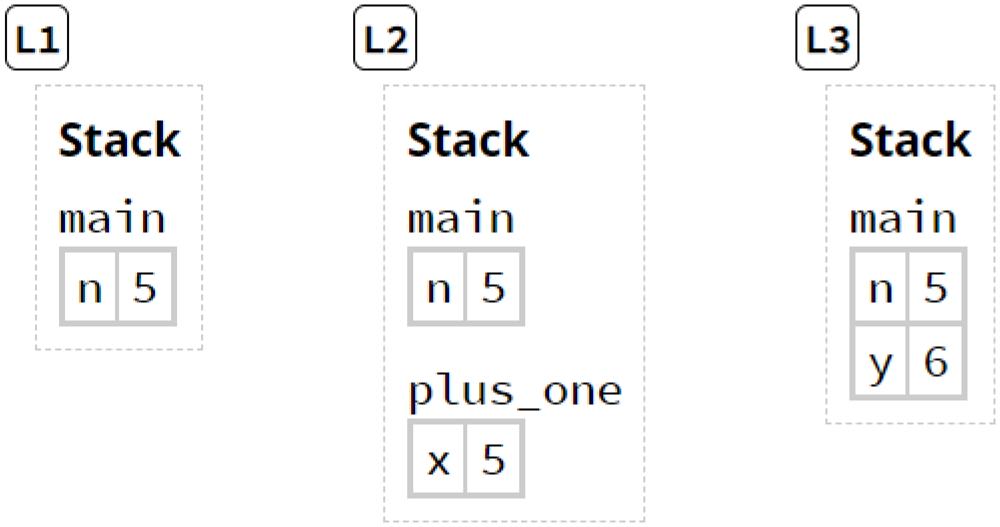


- Rust uses a value model of variables, like C/C++
  - Any typed data that is currently in use (i.e. *live*) is a value
  - A value's *lifetime* lasts from when is allocated until it is freed
- Value allocation
  - on the stack if lifetime matches a function call and size is known
  - on the heap otherwise
- Invariant: every value has exactly one *owner*
  - A variable
  - Some other value that is (or contains) a smart pointer
- Values on the heap are reclaimed when they lose their owner
  - e.g. because their owning smart pointer goes out of scope, or is reassigned



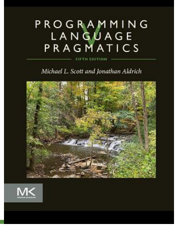
Conceptual model of variables of primitive types on the stack

```
fn main() {
    let n = 5; L1
    let y = plus_one(n); L3
    println!("The value of y is: {y}");
}

fn plus_one(x: i32) -> i32 {
    L2 x + 1
}
```



example from the Rust book (Brown version)

Assigning one variable to another copies the data if the type implements the Copy trait (includes `i32`)




```
let a = 5; L1
let mut b = a; L2
b += 1; L3
```

L1

Stack

main

a	5

L2

Stack

main

a	5
b	5

L3

Stack

main

a	5
b	6

But this is very expensive if the data is large →

```
let a = [0; 1_000_000]; L1
let b = a; L2
```

L1

Stack

main

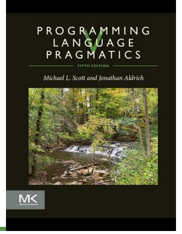
a	0	0	0	0	0	0	0	0	0	0	0	...	0

L2

Stack

main

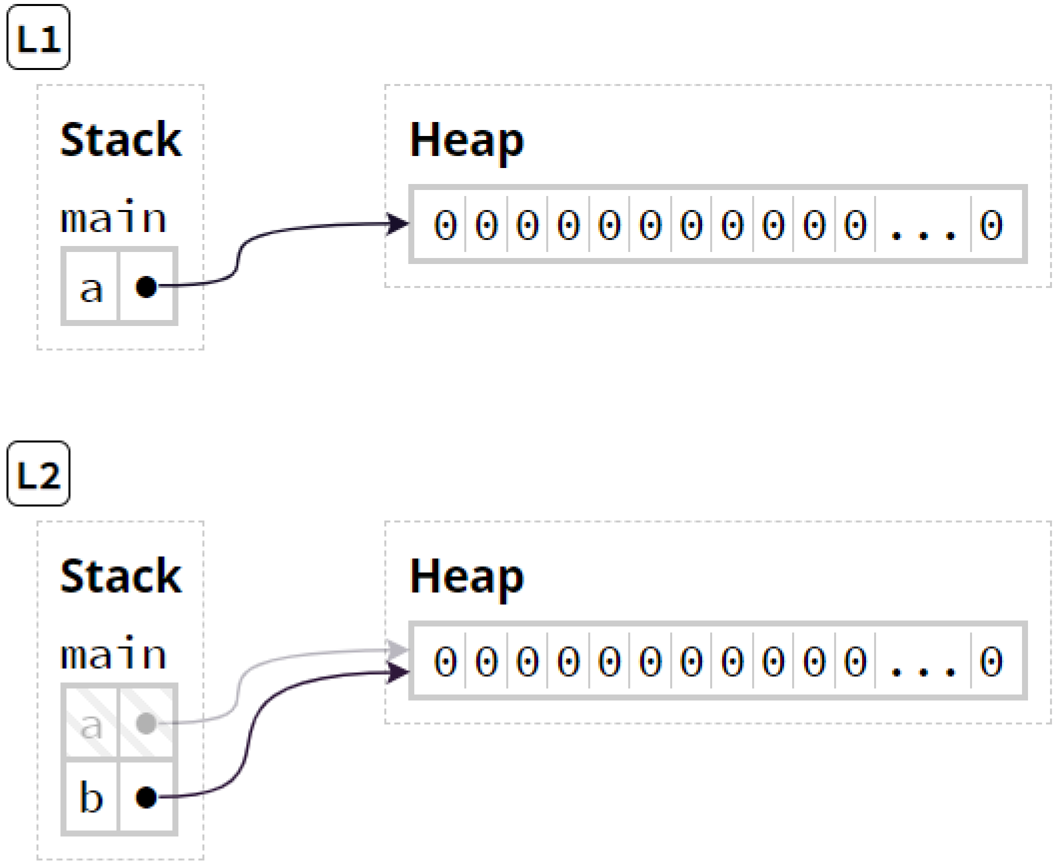
a	0	0	0	0	0	0	0	0	0	0	0	...	0
b	0	0	0	0	0	0	0	0	0	0	0	...	0



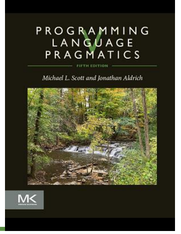
Boxes allocate memory in the heap

- Now a is of Box (pointer) type
- Assigning b to the value of a *moves* the pointer, because Box does not implement Copy
- We say that a *owns* the data before the move, and b owns it afterward
- We cannot use a after the move

```
let a = Box::new([0; 1_000_000]); L1
let b = a; L2
```



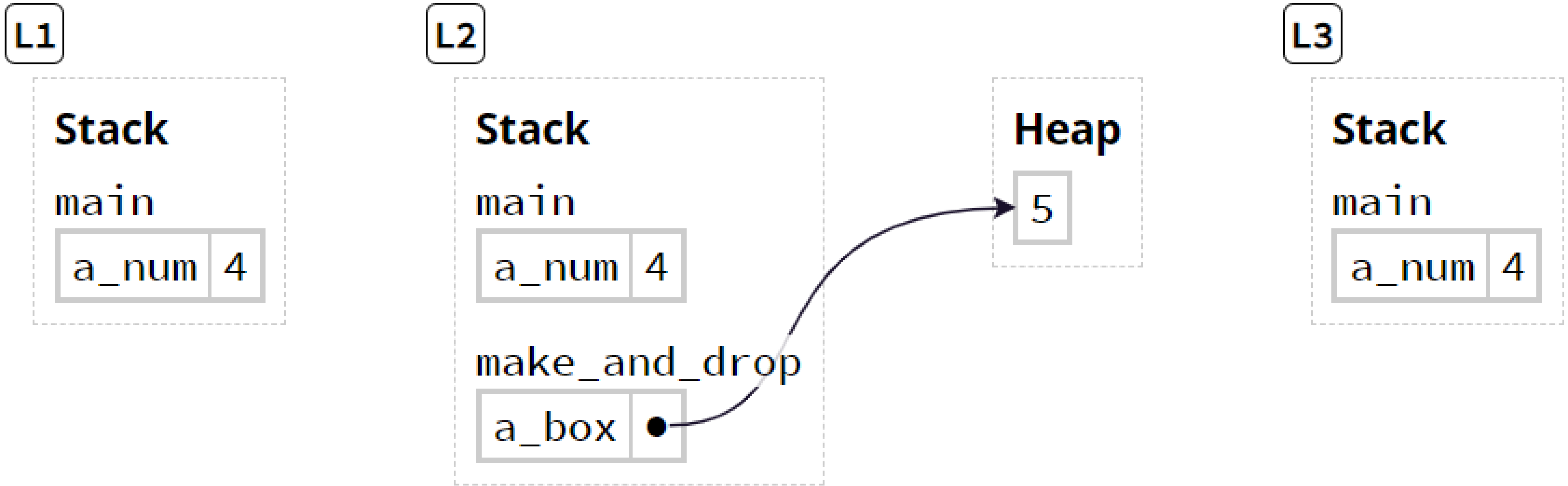
Owners deallocate boxes



If a variable owns a box, when Rust deallocates the variable's frame, then Rust deallocates ("drops") the box's heap memory.

The box holding 5 is deallocated at the end of `make_and_drop`

```
fn main() {
    let a_num = 4; L1
    make_and_drop(); L3
}

fn make_and_drop() {
    let a_box = Box::new(5); L2
}
```

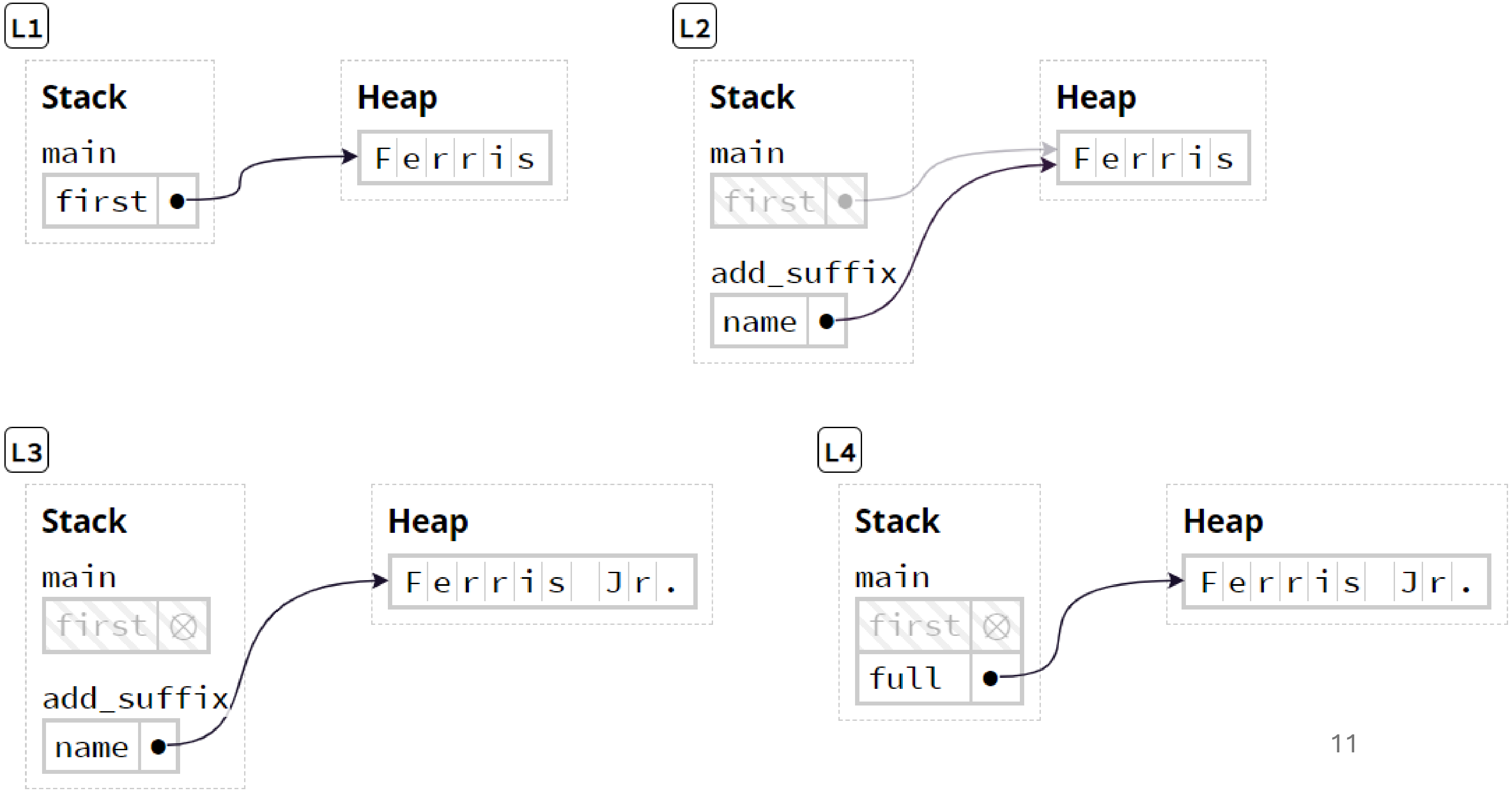


Ownership

Here's an example involving string manipulation

Note that it would be an error to use `first` after the pointer is moved in the call to `from`

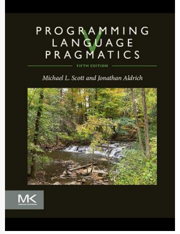
```
fn main() {
    let first = String::from("Ferris"); L1
    let full = add_suffix(first); L4
    println!("{full}");
}

fn add_suffix(mut name: String) -> String {
    L2 name.push_str(" Jr."); L3
    name
}
```

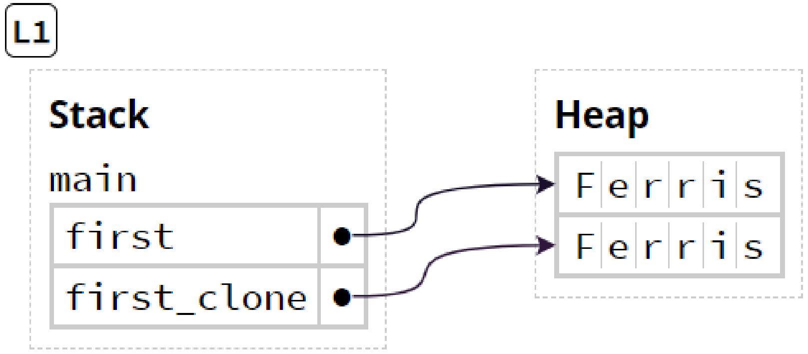


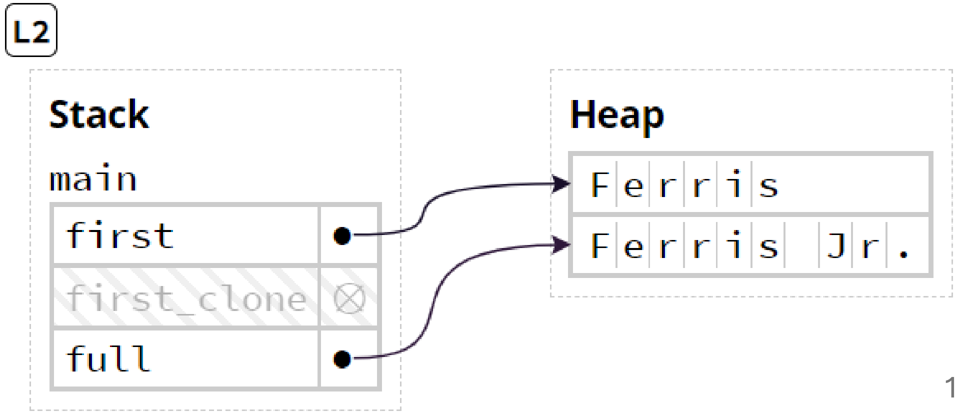
Cloning

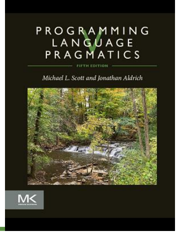
- If we want to continue to use the `first` string, we can *clone* it before moving the pointer
- The `clone` method makes a *deep copy* of the string (the data on the heap is copied, not just the pointer)

```
fn main() {
    let first = String::from("Ferris");
    let first_clone = first.clone(); L1
    let full = add_suffix(first_clone); L2
    println!("{full}, originally {first}");
}

fn add_suffix(mut name: String) -> String {
    name.push_str(" Jr.");
    name
}
```







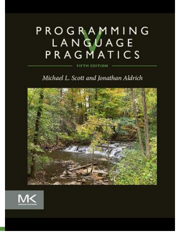


Ownership quiz

- Does this program compile? Why or why not?
- If it compiles, what is the result when it runs?

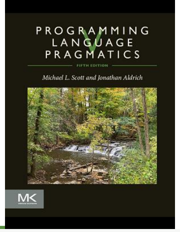
```
fn main() {
    let s = String::from("hello");
    let s2;
    let b = false;
    if b {
        s2 = s;
    }
    println!("{}", s);
}
```

Ownership quiz (SOLUTION)



- Does this program compile? Why or why not?
- Answer: no, it does not compile, because `s` might be moved to `s2` inside the `if` statement, so `s` cannot be used in the `println!` call.
- Rust doesn't try to figure out whether if statements will execute (that's undecidable in general)

```
fn main() {
    let s = String::from("hello");
    let s2;
    let b = false;
    if b {
        s2 = s;
    }
    println!("{}", s);
}
```

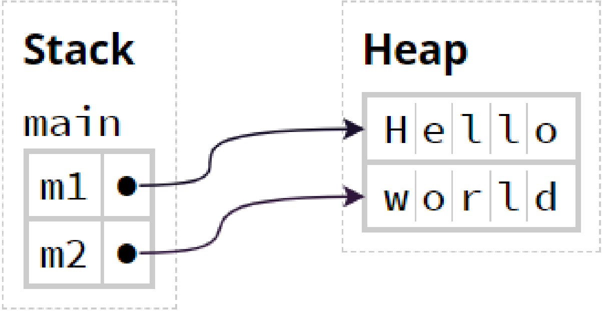


Using pointers after passing them to a function

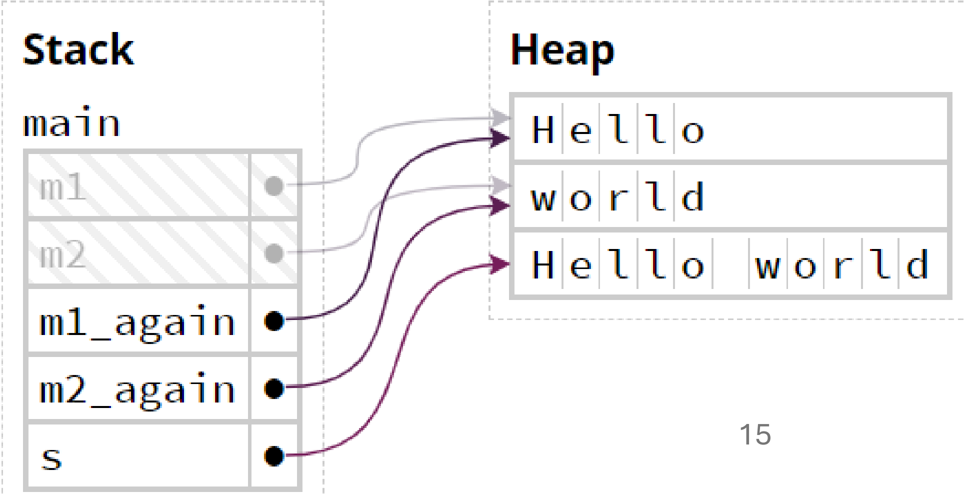
Moving owned pointers can be inconvenient

```
fn main() {
    let m1 = String::from("Hello");
    let m2 = String::from("world"); L1
    let (m1_again, m2_again) = greet(m1, m2);
    let s = format!("{} {}", m1_again, m2_again); L2
}

fn greet(g1: String, g2: String) -> (String, String) {
    println!("{} {}!", g1, g2);
    (g1, g2)
}
```

L1



L2

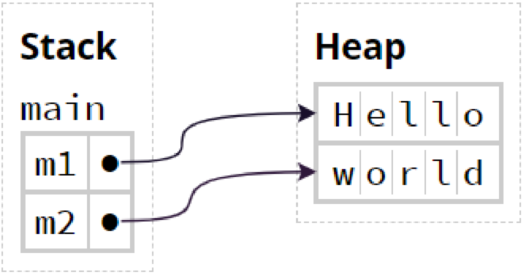


References

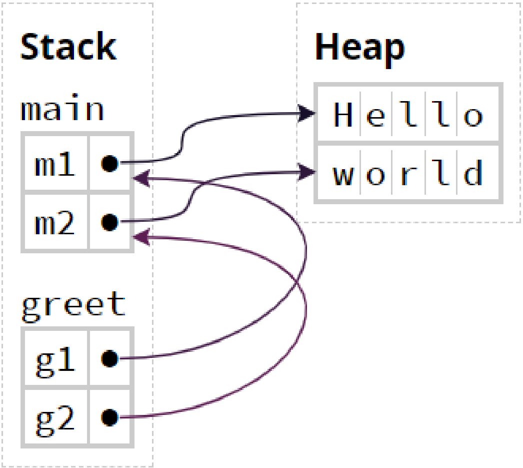
- A *reference* is a non-owning pointer
- The expression `&m1` *borrows* `m1`
- `g1` and `g2` are not deallocated at the end of `greet`, because they are not owned

```
fn main() {
    let m1 = String::from("Hello");
    let m2 = String::from("world"); L1
    greet(&m1, &m2); L3  // note the ampersands
    let s = format!("{} {}", m1, m2);
}

fn greet(g1: &String, g2: &String) { // note the ampersands
    L2 println!("{} {}!", g1, g2);
}
```

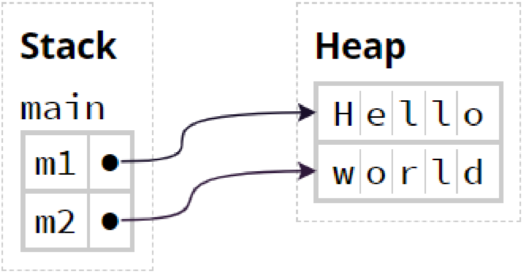
L1

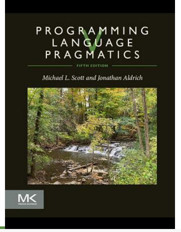


L2



L3



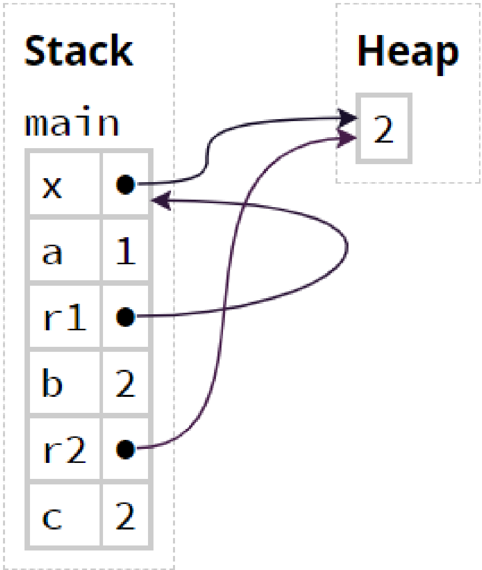


Dereferencing pointers

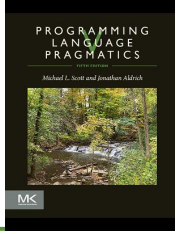
The * operator is used to access the data a pointer refers to

```
let mut x: Box<i32> = Box::new(1);
let a: i32 = *x;           // *x reads the heap value, so a = 1
*x += 1;                   // *x on the left-side modifies the heap value,
                           //     so x points to the value 2

let r1: &Box<i32> = &x;    // r1 points to x on the stack
let b: i32 = **r1;         // two dereferences get us to the heap value

let r2: &i32 = &*x;        // r2 points to the heap value directly
let c: i32 = *r2; L1       // so only one dereference is needed to read it
```

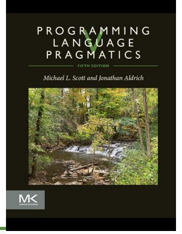
L1



Rust inserts (de)references automatically when the . operator is used



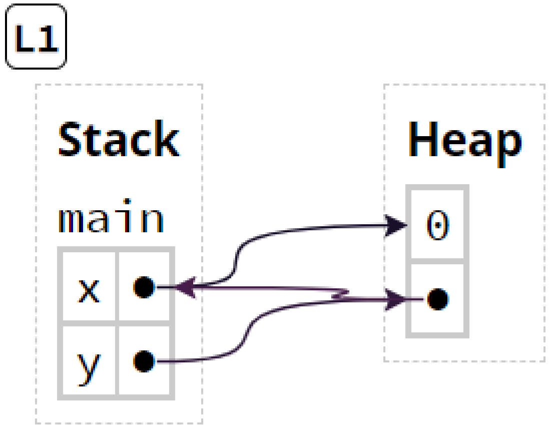

```
let x: Box<i32> = Box::new(-1);
let x_abs1 = i32::abs(*x); // explicit dereference
let x_abs2 = x.abs();      // implicit dereference
assert_eq!(x_abs1, x_abs2);

let r: &Box<i32> = &x;
let r_abs1 = i32::abs(**r); // explicit dereference (twice)
let r_abs2 = r.abs();       // implicit dereference (twice)
assert_eq!(r_abs1, r_abs2);

let s = String::from("Hello");
let s_len1 = str::len(&s); // explicit reference
let s_len2 = s.len();      // implicit reference
assert_eq!(s_len1, s_len2);
```



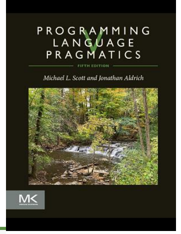
(De)referencing quiz

- Consider the following program, showing the state of memory after the last line:

```
let x = Box::new(0);
let y = Box::new(&x); L1
```

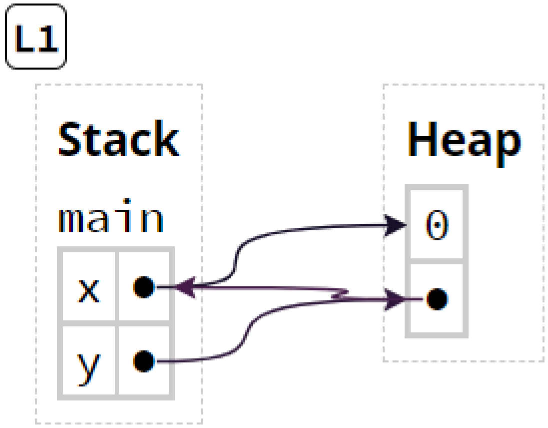


- If you wanted to copy out the number 0 through y, how many dereferences would you need to use?
  - For example, if the correct expression is *y, then the answer is 1.

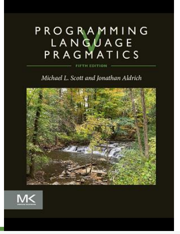


(De)referencing quiz (SOLUTION)

```
let x = Box::new(0);
let y = Box::new(&x); L1
```



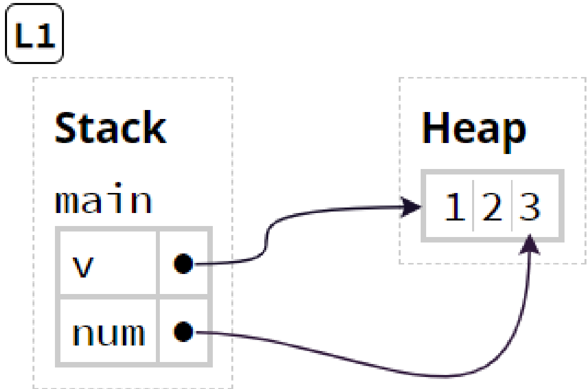
- Consider the following program, showing the state of memory after the last line:
- If you wanted to copy out the number 0 through y, how many dereferences would you need to use?
  - For example, if the correct expression is *y, then the answer is 1.
- Answer: 3 (***y)
  - One dereference for each pointer in the diagram
  - Also: one for each new, one for each &

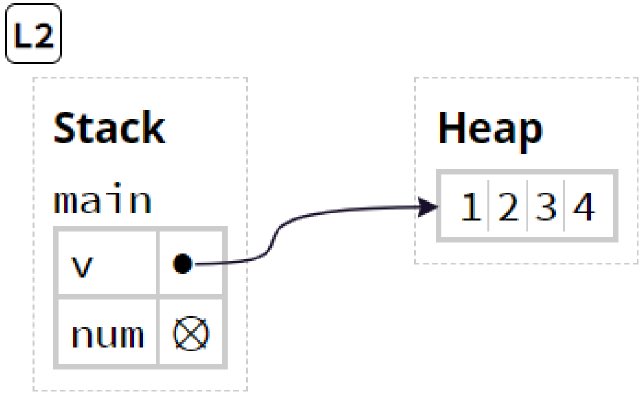


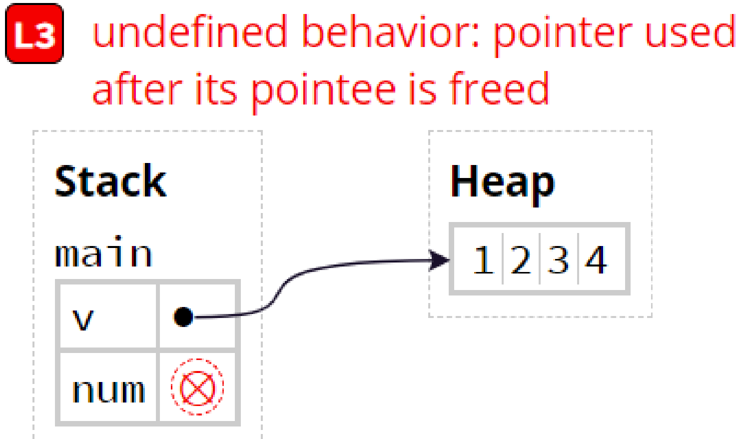
Rust prohibits simultaneous aliasing and mutation

- At L2, the alias num points to v[2]
- We write to v at L2 and read from num at L3
- This is a problem because the Vec's memory is re-allocated at L2, so the pointer used at L3 points to deallocated memory. Undefined behavior!

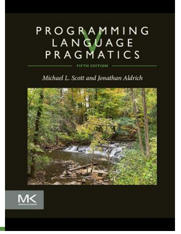
```
let mut v: Vec<i32> = vec![1, 2, 3];
let num: &i32 = &v[2]; L1
v.push(4); L2
println!("Third element is {}", *num); L3
```





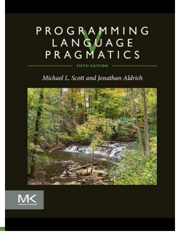


"Puzzled Ferris" means this code does not compile



Rust's ***borrow checker*** ensures reference safety

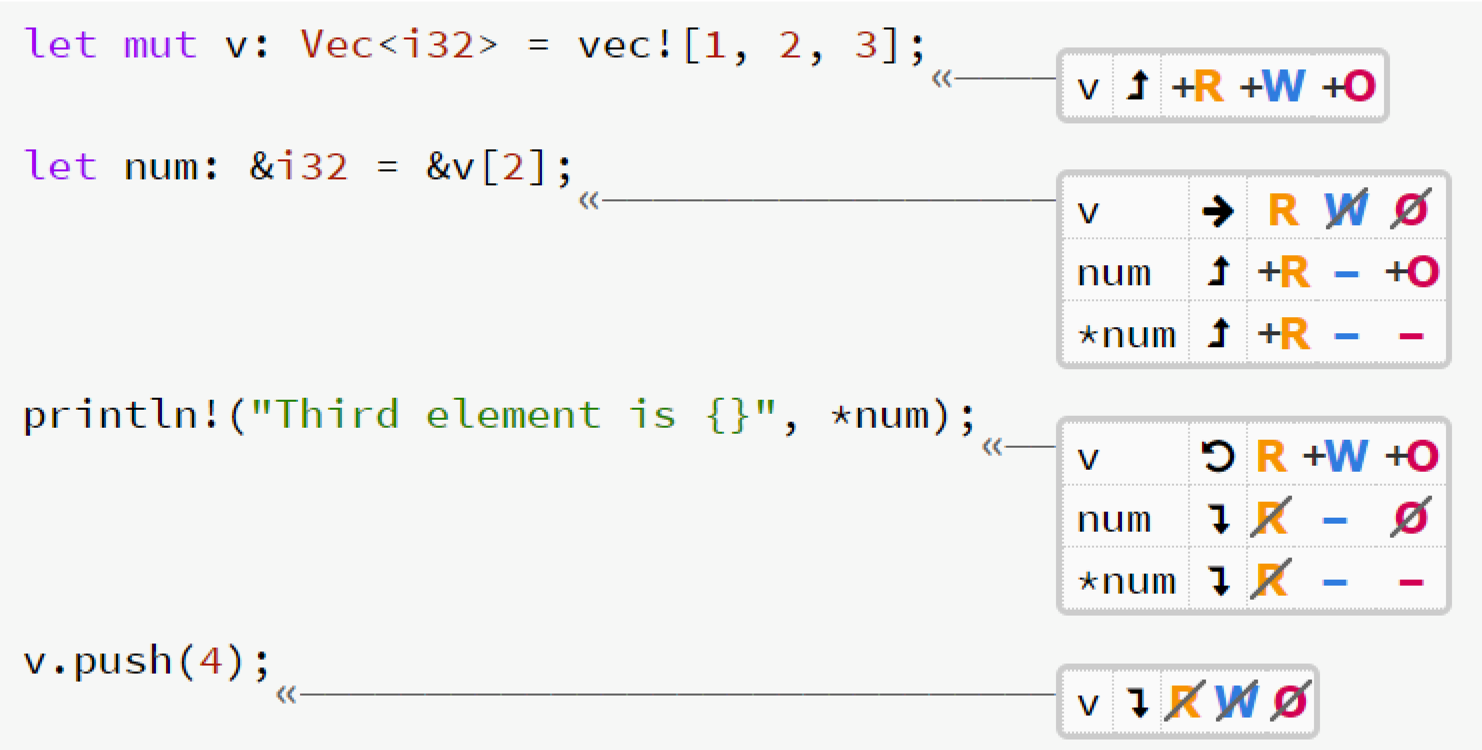
- Ensures that data is never aliased and mutated at the same time
- Tracks the permissions associated with each variable:
  - **Read** (**R**): data can be copied to another location.
  - **Write** (**W**): data can be mutated in-place (`let mut` vars)
    - Invariant: there can be at most one **W** permission to a piece of data at any time
  - **Own** (**O**): data can be moved or dropped.
- Creating a reference can temporarily remove these permissions



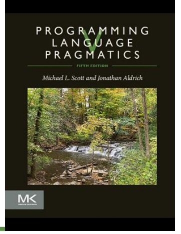
Example: how borrow checking works

Notes:

- Different permissions for num and *num
  - manipulating the reference vs. accessing the data
- Permissions are defined on *paths*
  - num, *num, `v[2]`, `a.field`, `*((*a)[0].1)`
- Permissions are lost when a mutually exclusive permission must be used
  - e.g. **W** on v is needed at `v.push(4)` so **R** on num is lost



A borrow checking error




```
let mut v: Vec<i32> = vec![1, 2, 3];
```

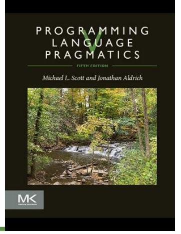
v	↥	+R	+W	+O

```
let num: &i32 = &R v[2];
```

v	→	R	~~W~~	~~O~~
num	↥	+R	–	+O
*num	↥	+R	–	–

```
v(R W).push(4);
println!("Third element is {}", *num);
```

```
error[E0502]: cannot borrow `v` as mutable because it is also borrowed as immutable
 --> test.rs:4:1
  |
3 | let num: &i32 = &v[2];
  |                 - immutable borrow occurs here
4 | v.push(4);
  | ^^^^^^^^^ mutable borrow occurs here
5 | println!("Third element is {}", *num);
  |                                 ---- immutable borrow later used here
```



We can also borrow mutably with &mut

```
let mut v: Vec<i32> = vec![1, 2, 3];

let num: &mut i32 = &mut v[2];

*num += 1;
println!("Third element is {}", *num);

println!("Vector is now {:?}", v);
```

After `let mut v: Vec<i32> = vec![1, 2, 3];`

v	↥	+R	+W	+O

After `let num: &mut i32 = &mut v[2];`

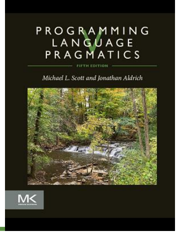
v	→	~~R~~	~~W~~	~~O~~
num	↥	+R	–	+O
*num	↥	+R	+W	–

After `println!("Third element is {}", *num);`

v	↻	+R	+W	+O
num	↧	~~R~~	–	~~O~~
*num	↧	~~R~~	~~W~~	–

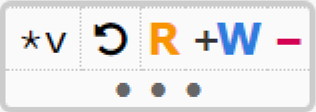
After `println!("Vector is now {:?}", v);`

v	↧	~~R~~	~~W~~	~~O~~



Permissions are returned when a reference's lifetime ends

```
fn ascii_capitalize(v: &mut Vec<char>) {
    let c = &v[0];

    if c.is_ascii_lowercase() {
        let up = c.to_ascii_uppercase();

        v[0] = up;
    } else {

        println!("Already capitalized: {:?}", v);
    }
}
```



- Control flow can make this interesting!

Borrowing quiz

In the example, explain why `strs` loses and regains write (W) permissions

```rust
fn get_first(v: &Vec<String>) -> &str {
    &v[0]
}

fn main() {
    let mut strs = vec![
        String::from("A"), String::from("B")
    ];

    let first = get_first(&strs);

    if first.len() > 0 {
        strs.push(String::from("C"));
    }
}
```

After `fn get_first(v: &Vec<String>) -> &str {`:

v	↑	+R	–	+O
*v	↑	+R	–	–

After `&v[0]`:

v	↓	~~R~~	–	~~O~~
*v	↓	~~R~~	–	–

After `let mut strs = vec![...];`:

strs	↑	+R	+W	+O

After `let first = get_first(&strs);`:

strs	→	R	~~W~~	~~O~~
first	↑	+R	–	+O
*first	↑	+R	–	–

After `if first.len() > 0 {`:

strs	↻	R	+W	+O
first	↓	~~R~~	–	~~O~~
*first	↓	~~R~~	–	–

After `strs.push(String::from("C"));`:

strs	↓	~~R~~	~~W~~	~~O~~

After `}`:

strs	↓	~~R~~	~~W~~	~~O~~

Borrowing quiz

In the example, explain why `strs` loses and regains write (W) permissions

ANSWER: `get_first` returns an immutable reference to data within `strs`, so `strs` is not writable while `first` is live

```
fn get_first(v: &Vec<String>) -> &str {
    &v[0]
}

fn main() {
    let mut strs = vec![
        String::from("A"), String::from("B")
    ];
    let first = get_first(&strs);
    if first.len() > 0 {
        strs.push(String::from("C"));
    }
}
```

After `fn get_first(v: &Vec<String>) -> &str {`

v	↑	+R	–	+O
*v	↑	+R	–	–

After `&v[0]`

v	↓	~~R~~	–	~~O~~
*v	↓	~~R~~	–	–

After `];`

strs	↑	+R	+W	+O

After `let first = get_first(&strs);`

strs	→	R	~~W~~	~~O~~
first	↑	+R	–	+O
*first	↑	+R	–	–

After `if first.len() > 0 {`

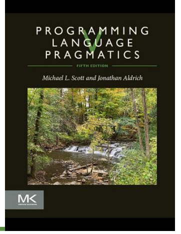
strs	↻	R	+W	+O
first	↓	~~R~~	–	~~O~~
*first	↓	~~R~~	–	–

After `strs.push(String::from("C"));`

strs	↓	~~R~~	~~W~~	~~O~~

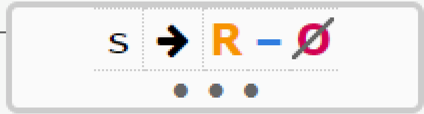
After `}`

strs	↓	~~R~~	~~W~~	~~O~~

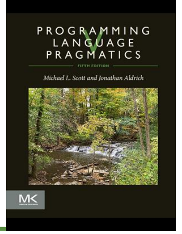


Invariant: data must outlive its references

```
let s = String::from("Hello world");

let s_ref = &s;


drop(s);
println!("{}", s_ref);
```



- The drop function explicitly releases a data structure
  - Any pointers in the data structure will be freed
- But drop requires an ownership (O) permission and we do not have that for s while s_ref is live



Fixing borrow checking errors

- The following code has a borrow error:

```
/// Returns a person's name with "Ph.D." added as a title
fn award_phd(name: &String) -> String {
    let mut name = *name;
    name.push_str(", Ph.D.");
    name
}
```

- What's the best fix?

A

```
fn award_phd(name: &String) -> String {
    let mut name = name.clone();
    name.push_str(", Ph.D.");
    name
}
```

B

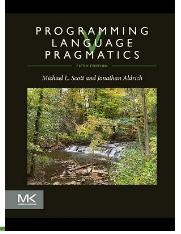
```
fn award_phd(mut name: String) -> String {
    name.push_str(", Ph.D.");
    name
}
```

C

```
fn award_phd(name: &mut String) {
    name.push_str(", Ph.D.");
}
```

D

```
fn award_phd(name: &String) -> String {
    let mut name = &*name;
    name.push_str(", Ph.D.");
    name
}
```

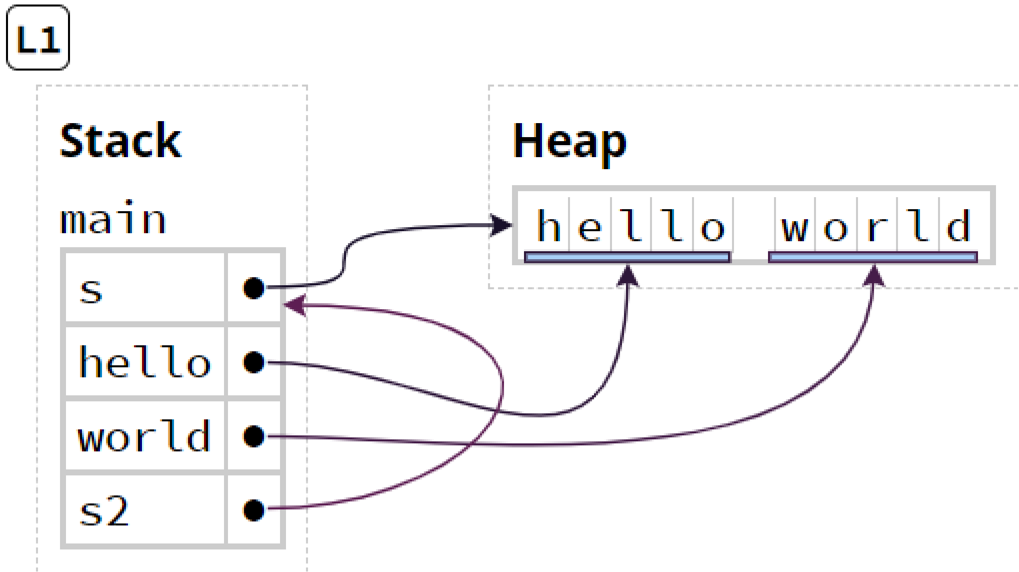


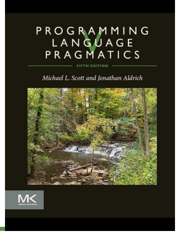
String slices

- A string slice of type `&str` points to a range of characters in a string
  - `&str` is the type of string literals in Rust!
- A slice knows its length—access beyond the length is a run time error
- Slices are references, so taking a slice changes the permission to the underlying data
  - If s were `mut` then we couldn't mutate it while `hello` is live
- You can also take slides of arrays

```
let a = [1, 2, 3, 4, 5];
let slice : &[i32] = &a[1..3];
```

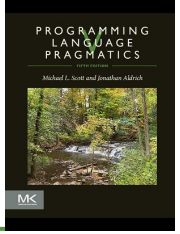
```
let s = String::from("hello world");

let hello: &str = &s[0..5];
let world: &str = &s[6..11];
let s2: &String = &s;  L1
```





Sometimes Rust can’t tell the lifetime of a reference

```rust
// does longest return x or y?
// unclear -- and it matters if they have different lifetimes
fn longest(x: &str, y: &str) -> &str {
    if x.len() > y.len() { x } else { y }
}

fn main() {
    let string1 = String::from("abcd");
    let string2 = "xyz";
    let result = longest(string1.as_str(), string2);
    println!("The longest string is {result}");
}
```

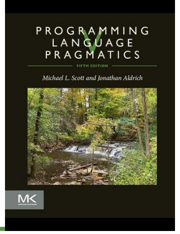


Lifetime annotations can help

```
&i32         // a reference
&'a i32      // a reference with an explicit lifetime
&'a mut i32 // a mutable reference with an explicit lifetime
```

- We don't need to write lifetime annotations everywhere—just when we need to compare the lifetimes of different references (e.g. in a function signature)

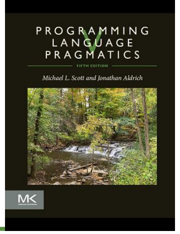
Using lifetime annotations




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

- This signature tells Rust that for some lifetime `'a`, the arguments must live at least as long as `‘a`.
- Also, the value returned by `longest` will live at least as long as `'a`.

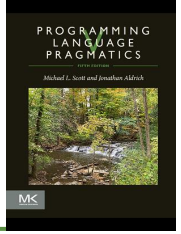
We can put lifetime annotations in structs




```rust
struct ImportantExcerpt<'a> { part: &'a str, }
fn main() {
  let novel = String::from("Call me Ishmael. Some years ago...");
  let first_sentence = novel.split('.').next().unwrap();
  let i = ImportantExcerpt { part: first_sentence, };
}
```

- The lifetime parameter of `ImportantExcerpt` tracks how long the `part` reference lives.
- Rust checks that `i` isn't used after `novel` goes out of scope

Lifetime annotations can often be elided



- If you don’t provide them, Rust acts as if they were specified according to the following rules
  - Every lifetime in the input type gets its own lifetime parameter

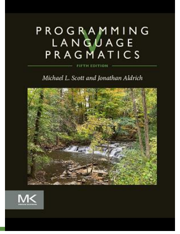
```
fn foo(x: &i32, y: &i32) → foo<'a, 'b>(x: &'a i32, y: &'b i32)
```

  - If there is exactly one lifetime parameter, that lifetime is assigned to all output lifetime parameters

```
fn foo(x: &i32) -> &i32 → fn foo<'a>(x: &'a i32) -> &'a i32
```

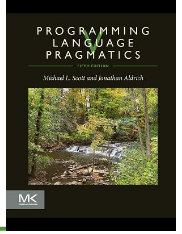
  - [Methods only]: If there are multiple input lifetime parameters, but one of them is `&self` or `&mut self`, that lifetime is used for all output lifetime parameters

The `'static` lifetime



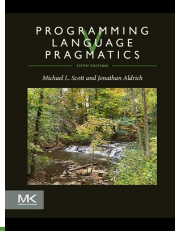
- The `'static` lifetime is for things that live for the entire execution of the program
  - Example: string literals
- Only use it if you know the underlying data lives indefinitely!

More about `Drop`



- When a value goes out of scope, we say it is *dropped*
  - If the value's type implements the `Drop` trait, the `drop` function is called
- Every heap allocated value is owned by exactly one box
  - Initially the box that allocates it
  - Ownership is transferred if one variable is assigned to another
    - the old box variable cannot be used
- Every box value is dropped exactly once
  - its drop function deallocates the heap data it owns
- Because of unique ownership
  - there cannot be any memory leaks
  - there cannot be any dangling pointers

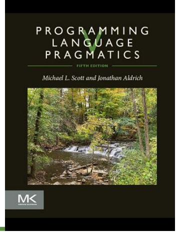
We can define binary trees with Box



- We use a struct to define a tree node with a key and left and right subtrees
- Rust does not have null pointers, so we use *options*
  - An `Option` is either `Some` (storing a value) or `None` (no value, like `null`)
  - In this case, the option holds a `Box<TNode>` since the subtree is allocated separately

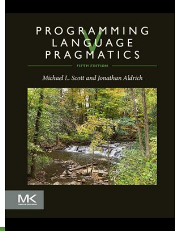
```
struct TNode {
  key: i32,
  left: Tree,
  right: Tree,
}
type Tree = Option<Box<TNode>>;
```

Now we define `insert`




```
struct TNode {
  key: i32,
  left: Tree,
  right: Tree,
}
type Tree = Option<Box<TNode>>;
fn insert(tree: &mut Tree, key: i32) {
  match tree {
    None => {
      *tree = Some(Box::new(TNode { key, left: None, right: None }))
    },
    Some(t) => {
      if key < t.key {
        insert(&mut t.left, key)
      } else {
        insert(&mut t.right, key)
      }
    },
  }
}
```

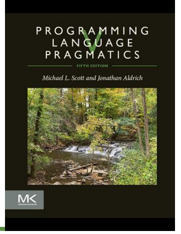
```
fn main() {
  let mut tree = None;
  insert(&mut tree, 5);
  insert(&mut tree, 3);
  insert(&mut tree, 4);
  insert(&mut tree, 10);
  // the whole tree is deallocated here
}
```



The Rc library allows sharing

- A value in the heap can only be pointed to by one box at a time
  - this is what enables us to avoid leaks and dangling references
  - but we can only create data structures like trees that have no sharing
- To create graphs, we need sharing in the heap
- The Rc library provides reference-counted shared pointers
  - The reference count is incremented and decremented when Rc pointers are created and dropped
  - When an Rc pointer is dropped and the reference count goes down to zero, the heap value is dropped and the storage is reclaimed

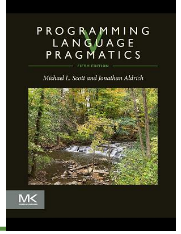
We can define graphs with Rc



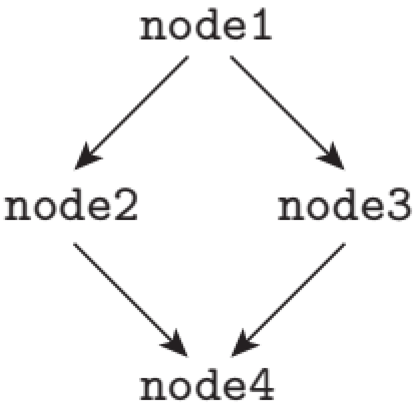

```
struct GNode {
  key: i32,
  edges: Vec<Edge>,
}

type Edge = Rc<RefCell<GNode>>;
```

- `Vec` is an expandable array type with bound checking
- Recall that Rust doesn't allow shared values to be mutable
  - But we want to change graph nodes, e.g. while building the graph
- `RefCell` implements unique, mutable borrowing
  - The contents can be borrowed temporarily
  - A run-time check verifies there are no other borrowers

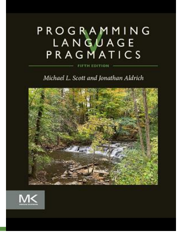
Now we can create a graph




```
struct GNode {
  key: i32,
  edges: Vec<Edge>,
}

type Edge = Rc<RefCell<GNode>>;

fn new_node(key: i32) -> Edge {
  Rc::new(RefCell::new(
    GNode { key,
            edges : Vec::new()
          }))
}
```

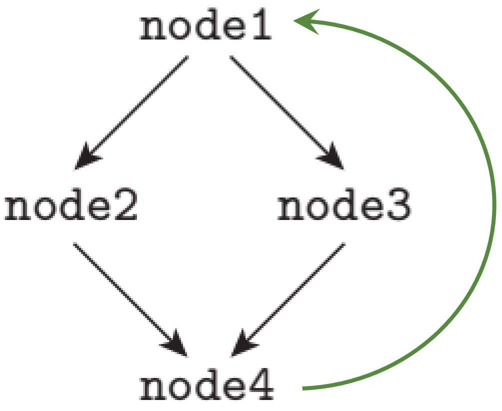



```
fn main() {
  let node1: Edge = new_node(1);
  let node2: Edge = new_node(2);
  let node3: Edge = new_node(3);
  let node4: Edge = new_node(4);
  node1.borrow_mut().edges.push(node2.clone());
  node1.borrow_mut().edges.push(node3.clone());
  node2.borrow_mut().edges.push(node4.clone());
  node3.borrow_mut().edges.push(node4.clone());
}
```

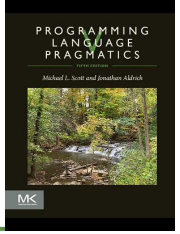


Cyclic graphs won’t be collected

```
struct GNode {
  key: i32,
  edges: Vec<Edge>,
}

type Edge = Rc<RefCell<GNode>>;

fn new_node(key: i32) -> Edge {
  Rc::new(RefCell::new(
    GNode { key,
            edges : Vec::new()
          }))
}
```




```
fn main() {
  let node1: Edge = new_node(1);
  let node2: Edge = new_node(2);
  let node3: Edge = new_node(3);
  let node4: Edge = new_node(4);
  node1.borrow_mut().edges.push(node2.clone());
  node1.borrow_mut().edges.push(node3.clone());
  node2.borrow_mut().edges.push(node4.clone());
  node3.borrow_mut().edges.push(node4.clone());
  node4.borrow_mut().edges.push(node1.clone());
}
```



Rust provides safe manual memory management

- It does so by enforcing 3 invariants
  - every value has exactly one *owner*
  - there can be at most one **W** permission to a piece of data at any time
  - data must outlive its references