

# A Tour of Rust

the programming language

Jim Fawcett

<https://JimFawcett.github.io>

<https://jimfawcett.github.io/Resources/RustTour.pdf>

# Tour Prologue

[https://JimFawcett.github.io/RustStory\\_Models.html](https://JimFawcett.github.io/RustStory_Models.html)

- Rust is an interesting and ambitious language, similar to C++, but with some unique differences.
  - Compiles to native code, no need for garbage collection
  - Emphasis on performance
- Rust features:
  - Type Safety – unable to create undefined behavior, by construction
    - Ownership model for all values
  - Objects
    - The language provides the usual set of primitive types
    - All library and user types are created from structs and enums
  - Generics
    - Similar to Java and C# generics, rust has broad support for trait constraints
- Rust tool chain provides Cargo, a package manager, builder, and executor

# Why Rust?

- Memory Safety
  - No dangling pointers or null references
  - No reading or writing to unowned memory
  - Rust's type system enforces sane ownership policies.
- No Data Races
  - The same ownership policies applied to thread interactions ensures data race free operation
- Performance
  - As fast as C and C++
- Abstraction without Overhead
  - Traits and Trait objects
  - In the same ballpark as C++

# Hello Rust World!

- This section assumes you have no experience with Rust.
- Getting started:
  - Install Rust - <https://www.rust-lang.org/tools/install>
  - This takes just a few minutes
  - Puts cargo, Rust's package manager, builder, executer on your path
  - Install Visual Studio Code - <https://code.visualstudio.com/download>
- Now we're ready for a hello world ++ experiment.
  - Create a temporary directory and navigate to that in a command prompt.
  - Issue command: `cargo new hello`
  - Issue command: `cd hello`
  - Issue command: `code .` [opens Visual Studio Code in hello directory]

# Hello World

```
x64 Native Tools Command Prompt for VS 2019

c:\temp>
cargo new hello
    Created binary (application) `hello` package

c:\temp>
cd hello

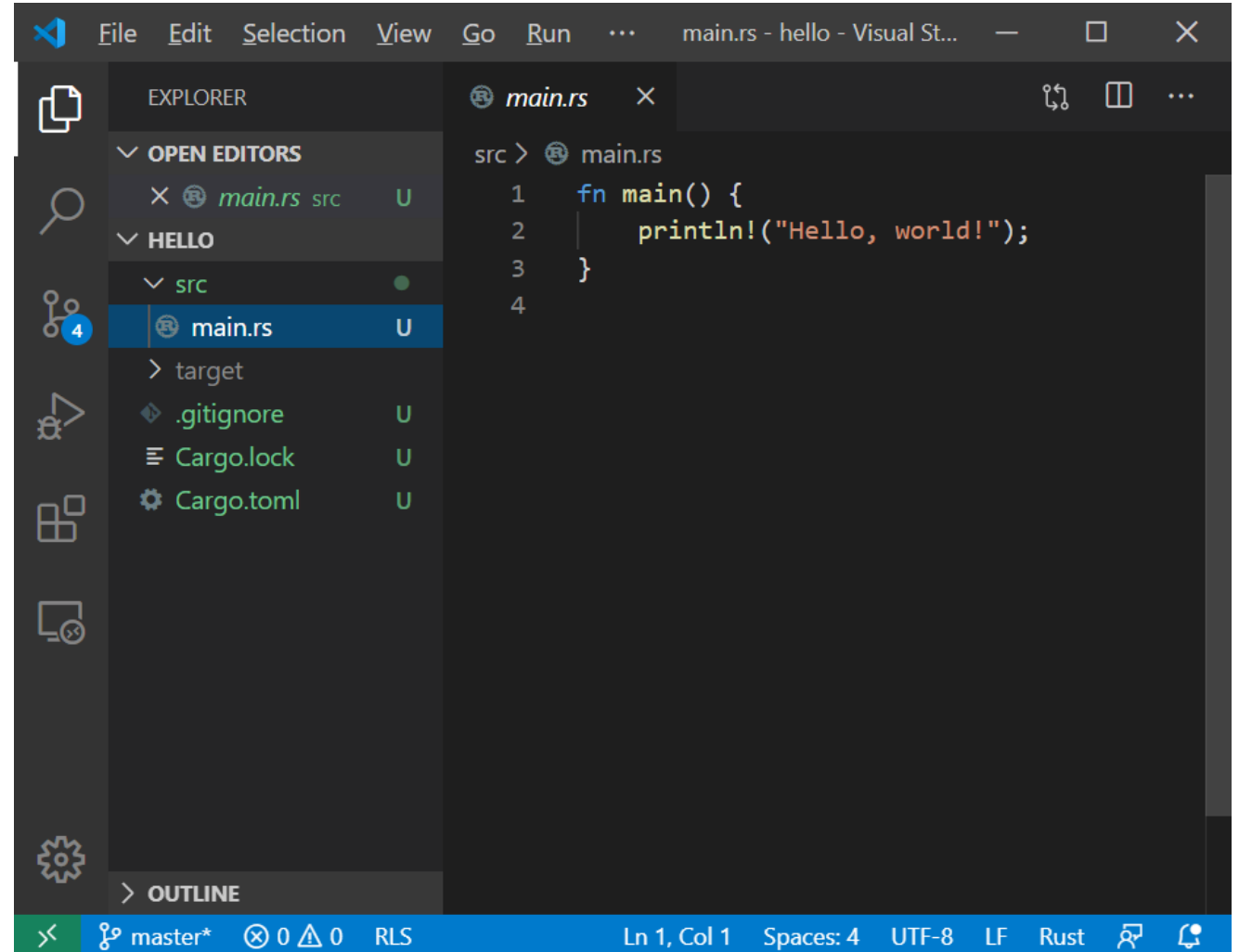
c:\temp\hello>
dir
Volume in drive C is OS
Volume Serial Number is 765A-DAD5

Directory of c:\temp\hello

03/29/2020  09:28 AM    <DIR>        .
03/29/2020  09:28 AM    <DIR>        ..
03/29/2020  09:28 AM                8 .gitignore
03/29/2020  09:28 AM            229 Cargo.toml
03/29/2020  09:28 AM    <DIR>        src
                2 File(s)            237 bytes
                3 Dir(s)  629,056,757,760 bytes free

c:\temp\hello>
code .

c:\temp\hello>
```



The screenshot shows the Visual Studio Code interface. The Explorer view on the left displays the project structure:

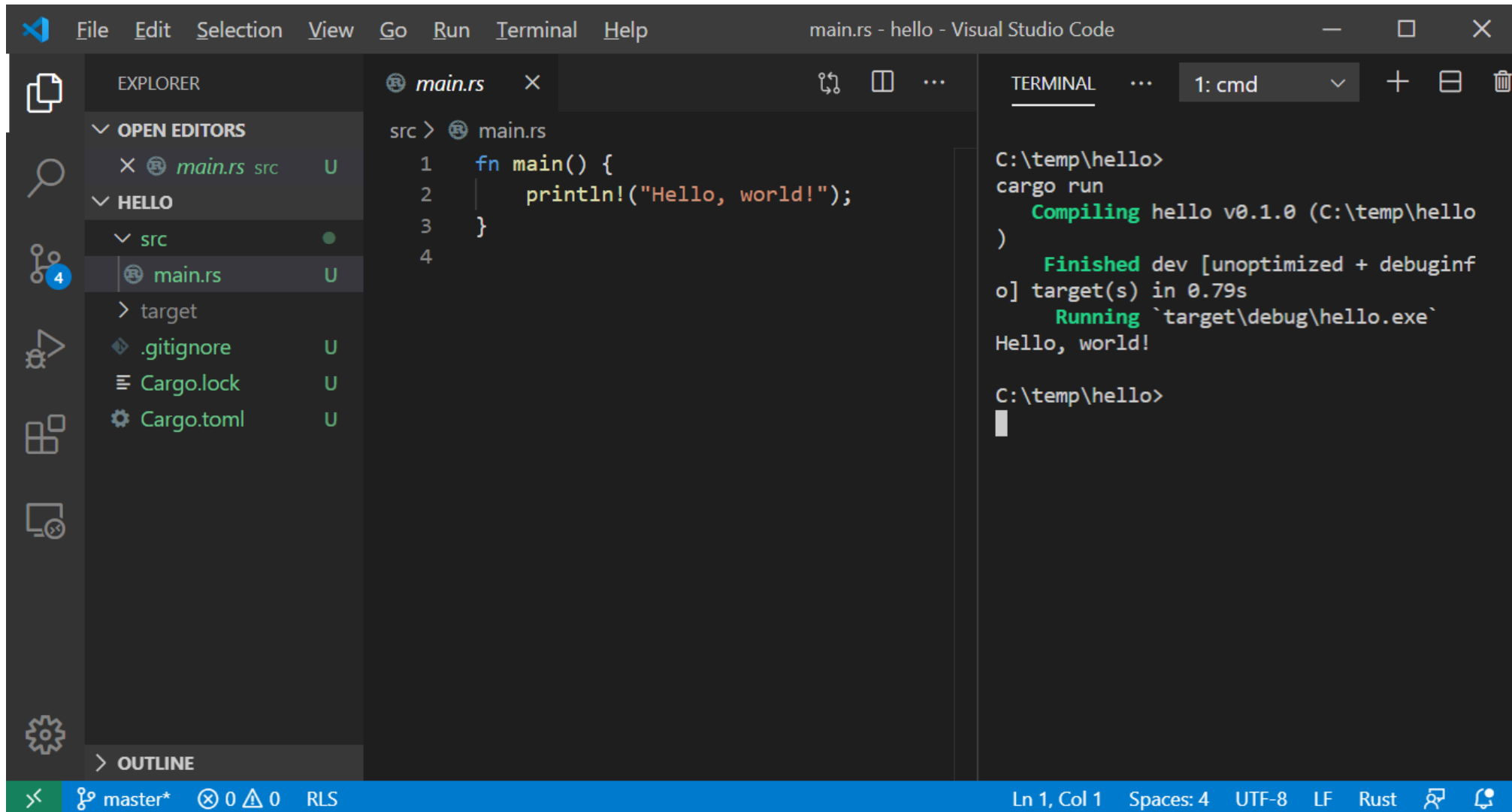
- EXPLORER
  - OPEN EDITORS
    - main.rs src U
  - HELLO
    - src
      - main.rs U
    - target
      - .gitignore U
      - Cargo.lock U
      - Cargo.toml U

The Editor view on the right shows the code for 'main.rs':

```
src > main.rs
1 fn main() {
2     println!("Hello, world!");
3 }
4
```

The status bar at the bottom indicates the current file is 'main.rs' in the 'src' directory, with the following details: master\*, 0 errors, 0 warnings, RLS, Ln 1, Col 1, Spaces: 4, UTF-8, LF, Rust.

# Building and Running with Cargo



The screenshot displays the Visual Studio Code interface with a Rust project named 'hello'. The Explorer panel on the left shows the project structure with 'src' containing 'main.rs'. The main editor shows the contents of 'main.rs', which defines a simple 'main' function that prints 'Hello, world!'. The Terminal panel on the right shows the execution of 'cargo run', which successfully compiles the program and runs it, outputting 'Hello, world!'.

```
File Edit Selection View Go Run Terminal Help main.rs - hello - Visual Studio Code
```

EXPLORER

- OPEN EDITORS
  - main.rs src U
- HELLO
  - src
    - main.rs U
  - target
    - .gitignore U
    - Cargo.lock U
    - Cargo.toml U
- OUTLINE

main.rs

```
src > main.rs
1 fn main() {
2     println!("Hello, world!");
3 }
4
```

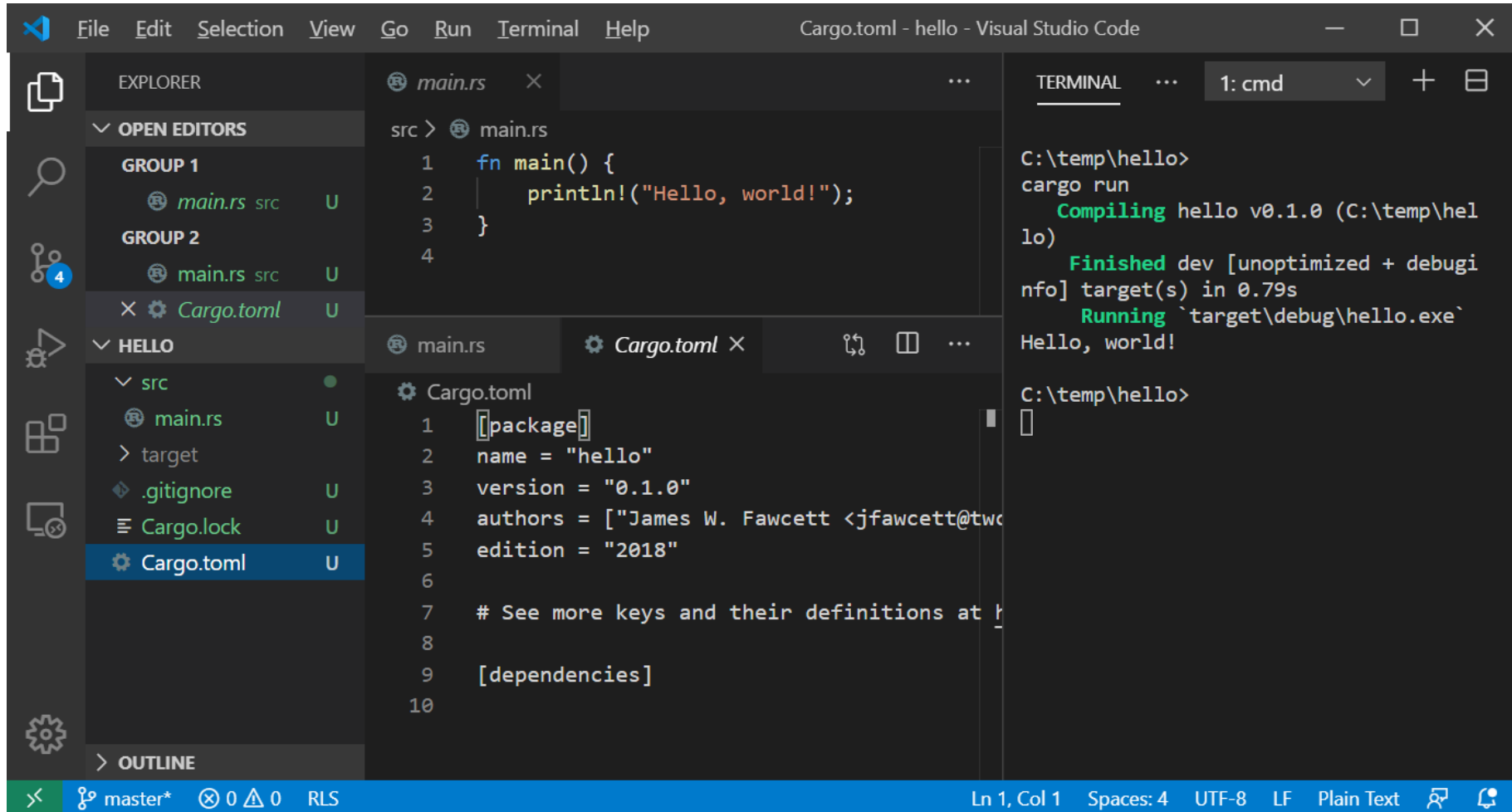
TERMINAL 1: cmd

```
C:\temp\hello>
cargo run
    Compiling hello v0.1.0 (C:\temp\hello)
    Finished dev [unoptimized + debuginfo] target(s) in 0.79s
    Running `target\debug\hello.exe`
Hello, world!

C:\temp\hello>
```

Ln 1, Col 1 Spaces: 4 UTF-8 LF Rust

# Cargo.toml – defines package



The screenshot displays the Visual Studio Code interface for a Rust project named 'hello'. The Explorer sidebar on the left shows the project structure, with 'Cargo.toml' highlighted under the 'src' directory. The main editor area shows two files: 'main.rs' and 'Cargo.toml'. 'main.rs' contains a simple Rust program that prints 'Hello, world!'. 'Cargo.toml' defines the package name as 'hello', version '0.1.0', and author 'James W. Fawcett'. The terminal on the right shows the command 'cargo run' being executed, which compiles the program and runs it, outputting 'Hello, world!'.

```
File Edit Selection View Go Run Terminal Help
Cargo.toml - hello - Visual Studio Code

EXPLORER
OPEN EDITORS
GROUP 1
  main.rs src U
GROUP 2
  main.rs src U
  Cargo.toml U
HELLO
  src
    main.rs U
    target
    .gitignore U
    Cargo.lock U
    Cargo.toml U
  OUTLINE

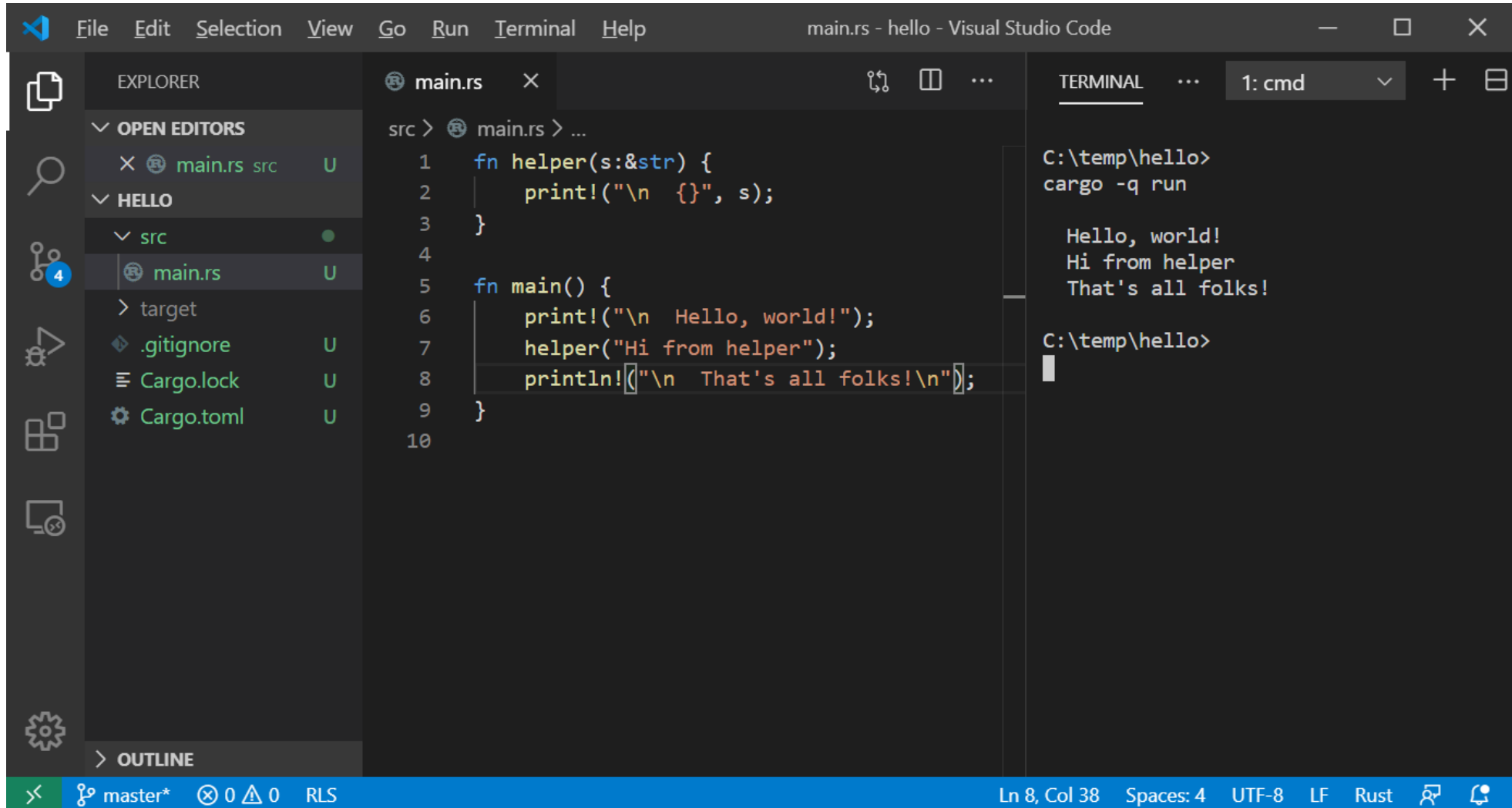
main.rs
src > main.rs
1 fn main() {
2     println!("Hello, world!");
3 }
4

Cargo.toml
1 [[package]]
2 name = "hello"
3 version = "0.1.0"
4 authors = ["James W. Fawcett <jfawcett@tw"]
5 edition = "2018"
6
7 # See more keys and their definitions at https://doc.rust-lang.org/cargo/reference/manifest.html
8
9 [dependencies]
10

TERMINAL
1: cmd
C:\temp\hello>
cargo run
Compiling hello v0.1.0 (C:\temp\hello)
Finished dev [unoptimized + debuginfo] target(s) in 0.79s
Running `target\debug\hello.exe`
Hello, world!

C:\temp\hello>
```

# Add another function



The screenshot shows the Visual Studio Code interface with a Rust project named 'hello'. The Explorer panel on the left shows the file structure with 'main.rs' selected. The main editor displays the code in 'main.rs', which includes a new 'helper' function and a call to it in the 'main' function. The output terminal on the right shows the successful execution of the program, displaying the expected output.

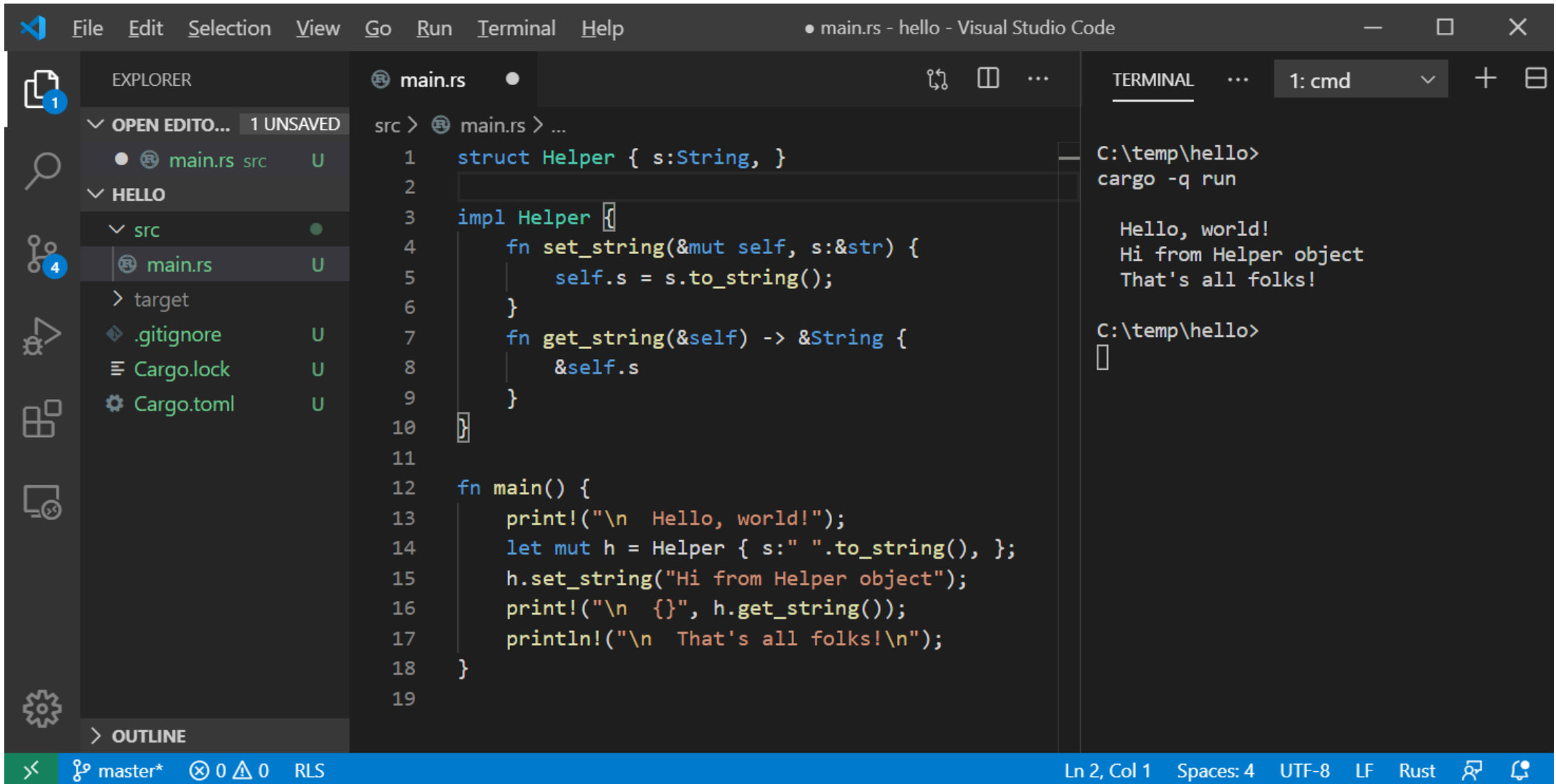
```
src > main.rs > ...
1  fn helper(s:&str) {
2      print!("\n {}", s);
3  }
4
5  fn main() {
6      print!("\n Hello, world!");
7      helper("Hi from helper");
8      println!("\n That's all folks!\n");
9  }
10
```

Output:

```
C:\temp\hello> cargo -q run
Hello, world!
Hi from helper
That's all folks!
C:\temp\hello>
```



# Modify to use “object”



The screenshot shows the Visual Studio Code interface with a Rust project named 'hello'. The Explorer panel on the left shows the project structure with 'main.rs' in the 'src' directory. The main editor displays the code for 'main.rs', which defines a 'Helper' struct and implements methods for setting and getting a string. The 'main' function creates a 'Helper' object, sets its string to 'Hi from Helper object', and prints it. The Terminal panel on the right shows the command 'cargo -q run' being executed, resulting in the output: 'Hello, world!', 'Hi from Helper object', and 'That's all folks!'.

```
File Edit Selection View Go Run Terminal Help
main.rs - hello - Visual Studio Code

EXPLORER
1 OPEN EDITOR... 1 UNSAVED
  main.rs src U
  HELLO
    src
      4 main.rs U
    target
    .gitignore U
    Cargo.lock U
    Cargo.toml U
  OUTLINE

main.rs
src > main.rs > ...
1 struct Helper { s:String, }
2
3 impl Helper {
4     fn set_string(&mut self, s:&str) {
5         self.s = s.to_string();
6     }
7     fn get_string(&self) -> &String {
8         &self.s
9     }
10 }
11
12 fn main() {
13     print!("\n Hello, world!");
14     let mut h = Helper { s:" ".to_string(), };
15     h.set_string("Hi from Helper object");
16     print!("\n {}", h.get_string());
17     println!("\n That's all folks!\n");
18 }
19

TERMINAL 1: cmd
C:\temp\hello>
cargo -q run

Hello, world!
Hi from Helper object
That's all folks!

C:\temp\hello>

```

Ln 2, Col 1 Spaces: 4 UTF-8 LF Rust

# Why Rust?

- Memory Safety
  - No dangling pointers or null references
  - No reading or writing to unowned memory
  - Rust's type system enforces sane ownership policies.
- No Data Races
  - The same ownership policies applied to thread interactions ensures data race free operation
- Performance
  - As fast as C and C++
- Abstraction without Overhead
  - Traits and Trait objects
  - In the same ballpark as C++

# Type Safety

- A program is well defined if no execution can exhibit undefined behavior.
- A language is type safe if its type system ensures that every program is well defined.
- A non-type safe language may introduce undefined behavior with:
  - Integer overflow, e.g., wrap-around
  - Buffer overflow – out of bounds access
  - Use after free – access unowned memory
  - Double free – corrupt memory manager
  - Race conditions – mutation without exclusive ownership

# Undefined Behavior – C++ dangling reference

The screenshot displays the Microsoft Visual Studio IDE with a C++ project named 'UndefinedBehavior'. The code in 'UndefBehavior.cpp' demonstrates a dangling reference by pushing back an element into a vector, which causes a reallocation and invalidates existing references. The output in the 'Microsoft Visual Studio Debug Console' shows the state of the program before and after the reallocation, highlighting the change in the memory address of the dangling reference.

```
16
17 int main() {
18
19     std::cout << "\n Demo of Undefined Behavior - dangling reference";
20     std::cout << "\n -----";
21
22     std::vector<int> v;
23     v.reserve(3);
24     std::cout << "\n capacity of v = " << v.capacity();
25     v.push_back(1);
26     v.push_back(2);
27     v.push_back(3);
28     showVec(v);
29     int& r1 = v[1];
30     std::cout << "\n address of v[1] = " << &v[1];
31     std::cout << "\n address of r1 = " << &r1;
32     std::cout << "\n value of r1 = " << r1;
33     v.push_back(4);
34     std::cout << "\n push_back caused reallocation";
35
36     showVec(v);
37     std::cout << "\n address of v[1] = " << &v[1];
38     std::cout << "\n address of r1 = " << &r1;
39     std::cout << "\n value of r1 = " << r1;
40     std::cout << std::endl;
41 }
```

Microsoft Visual Studio Debug Console

```
Demo of Undefined Behavior - dangling reference
-----
capacity of v = 3
1 2 3
address of v[1] = 014F503C
address of r1 = 014F503C
value of r1 = 2
push_back caused reallocation
1 2 3 4
address of v[1] = 014E5A9C
address of r1 = 014F503C
value of r1 = -572662307
```

# Undefined Behavior – C++ index out of bounds

The screenshot shows the Visual Studio IDE with a C++ project named 'UndefinedBehavior'. The code in 'UndefBehavior.cpp' is as follows:

```
42  
43     std::cout << "\n Demo of Undefined Behavior - out of bounds index";  
44     std::cout << "\n -----";  
45  
46     int array[3]{ 1, 2, 3 };  
47     std::cout << "\n ";  
48     for (size_t i = 0; i <= 3; ++i) {  
49         std::cout << array[i] << " ";  
50     }  
51     std::cout << std::endl;  
52 }
```

The code attempts to access `array[3]`, which is out of bounds for an array of size 3. The output window shows the following text:

```
Demo of Undefined Behavior - out of bounds index  
-----  
1 2 3 -858993460  
  
C:\su\temp\UndefinedBehavior\Debug\UndefinedBehavior.exe (process  
13708) exited with code 0.  
Press any key to close this window . . .
```

The status bar at the bottom indicates 'Ready' and 'Ln: 52 Ch: 2 SPC CRLF'.

# In defense of C++ - Dangling Reference

- If we had used an iterator:
  - `auto iter1 = ++v.begin();`
  - `v.push_back(4);`
  - `Std::cout << *iter1; // throws exception – no undefined behavior`
- It is standard practice to access containers with iterators, so well-crafted C++ will not exhibit undefined behavior.
- The difference:
  - With Rust you can't get undefined behavior (UB) – most often programs fail to compile if they would have UB.
  - C++ code has to be well-crafted to avoid UB, errors are discovered at run-time, not compile-time.

# In defense of C++ - Index out of Bounds

- If we had used a range-based for loop:

```
• for(auto item : array) {  
    std::cout << item << " ";  
}
```

there is no chance of out-of-bounds indexing

- It is standard practice to traverse containers with range-based for loops, so well-crafted C++ will not exhibit undefined behavior.
- The difference:
  - With Rust you can't get undefined behavior (UB) – out of bounds index causes panic (exit) with no chance to access unowned memory.
  - C++ code has to be well-crafted, using standard idioms, to avoid UB.

# Safe Type System - Rust

- Rust is a type safe language, avoiding undefined behavior.
- Rust's type system prevents data races in multi-threaded programs.
- Rust's type system ensures this behavior with its Ownership model:
  - Prevent mutation combined with aliasing
    - Ensure memory safety
  - Prevent mutation, aliasing, and lack of access ordering
    - Avoid data races



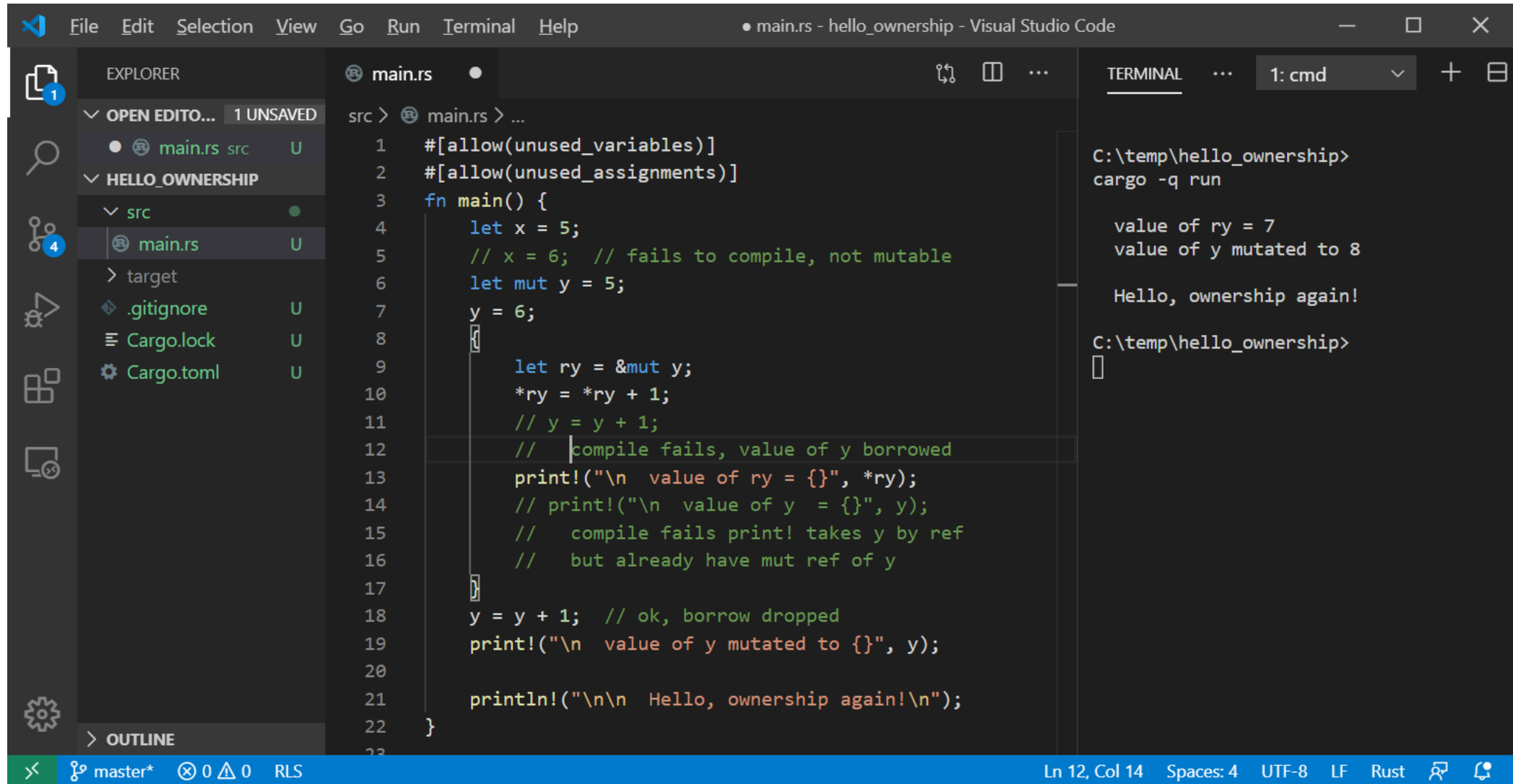
# Rust Ownership

- Ownership rules are, in principle, quite simple:
  - Rust enforces **Read-Write-Locks** on data access at compile-time.
  - Any number of readers may access value simultaneously.
  - Writers get exclusive access to value – no other readers or writers.
- What are readers and writers?
  - Any variable bound to a value with no mut qualifier is a reader.
    - Original owner: `let s = String::from("a string");`
    - References to the data: `let r = &s;`
  - Any variable bound to a value with mut qualifier is a writer:
    - Original owner: `let mut s = String::from("another string");`
    - References to the data: `let mut r = &s;`

# Hello Ownership!

- Rust's ownership policies:
  - Every value has one and only one owner
  - Ownership can be transferred with a move
  - Ownership can be borrowed with a reference
    - References hold a view into value
    - Original value's owner can't mutate value while borrowed
    - Immutable references can be shared
    - Mutable references are exclusive
    - Borrowing ends when reference goes out of scope or is dropped
    - This fits very well with pass by reference function arguments
  - Values are, by default, immutable, but can be made mutable
    - `let x = 3; // x is immutable`
    - `let mut y = 3; // y is mutable`

# Hello Rust Ownership



The screenshot shows the Visual Studio Code editor with a Rust file named `main.rs` open. The Explorer sidebar on the left shows the project structure: `src` containing `main.rs`, and other files like `.gitignore`, `Cargo.lock`, and `Cargo.toml`. The main editor displays the following Rust code:

```
src > main.rs > ...
1  #[allow(unused_variables)]
2  #[allow(unused_assignments)]
3  fn main() {
4      let x = 5;
5      // x = 6; // fails to compile, not mutable
6      let mut y = 5;
7      y = 6;
8      {
9          let ry = &mut y;
10         *ry = *ry + 1;
11         // y = y + 1;
12         // compile fails, value of y borrowed
13         println!("\n value of ry = {}", *ry);
14         // println!("\n value of y = {}", y);
15         // compile fails print! takes y by ref
16         // but already have mut ref of y
17     }
18     y = y + 1; // ok, borrow dropped
19     println!("\n value of y mutated to {}", y);
20
21     println!("\n\n Hello, ownership again!\n");
22 }
```

The Terminal panel on the right shows the command prompt output:

```
C:\temp\hello_ownership> cargo -q run

value of ry = 7
value of y mutated to 8

Hello, ownership again!

C:\temp\hello_ownership>
```

The status bar at the bottom indicates the current file is `main.rs`, the workspace is `hello_ownership`, and the Rust compiler is `rustc`. The status bar also shows the current line and column: `Ln 12, Col 14`.

# Copies, Moves

- Copy

- Data resides in one contiguous block of memory (blittable)
- `let x = 3.5;`
- `let y = x;`
- y gets copy of x's value ==> two separate locations holding the same value.
- **Copy binding creates new owner of new data.**

- Move

- Data resides in two or more blocks, usually one in stack, one in heap.
- `let s = String::from("a string");`
- `let t = s;`
- s value moved to t, s becomes invalid
- **Move binding transfers ownership**

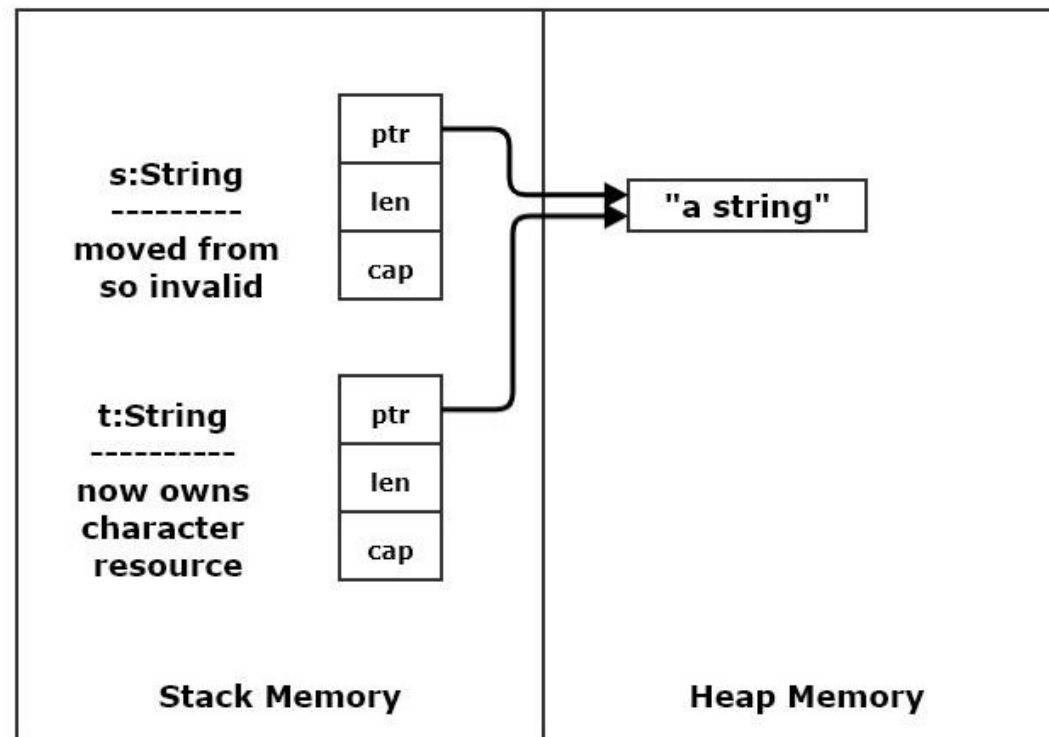
# Rust Move versus Copy

- Rust will copy any value contained in a single contiguous block of memory (blittable)

- `let x = 2;`
  - `let y = x; // copy`

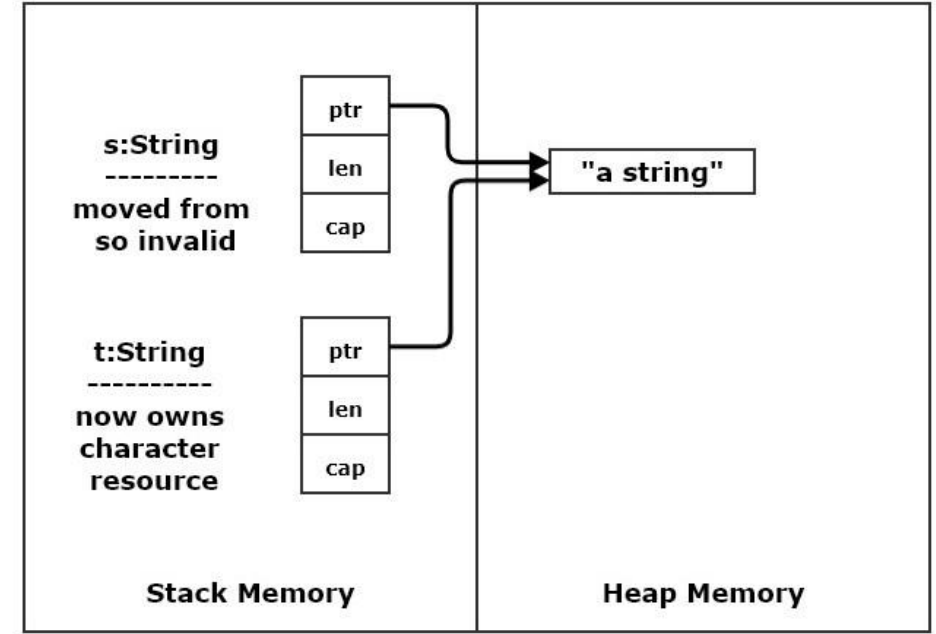
- Any value requiring separate parts, like the string shown in the right panel will be moved.

- `let s = String::from("a string");`
  - `let t = s;`  
    `// value moved from s`  
    `// t owns string, s invalid`



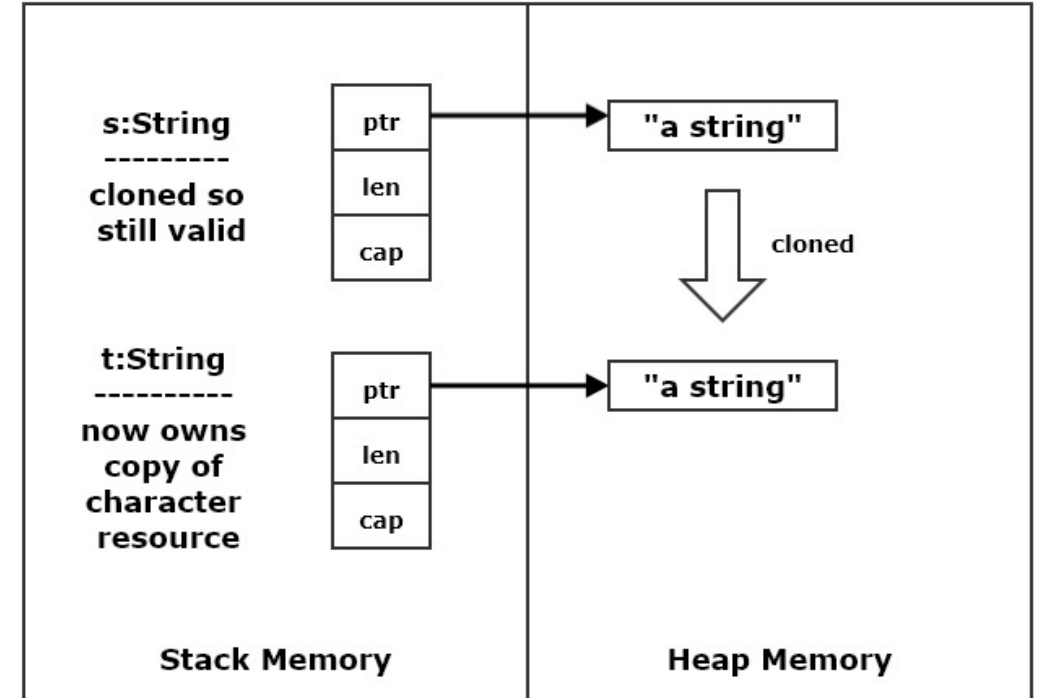
# Move

- `let s = String::from("a string");`
  - `s` consists of a control block in stack memory and a character array in the heap.
- `let t = s;`
  - `s`'s **control block** is blitted to `t`
  - That preserves the pointer to the heap character array.
  - So now `t` owns the string and `s` is marked as invalid.
- This is fast. Characters are not copied, only the small control block is copied.



# Rust Clone

- Often a type satisfies clone trait (if not you can add that).
- This allows moves to be avoided by explicitly calling clone() to make a copy.
  - `let t = s.clone();`  
`// s still valid`
- Clone must always be called explicitly. Rust wants you to know when you invoke an expensive operation.



# References and RwLocking

- Non-mutable Vec and references - all readers:
  - `let v = vec![1,2,3];`
  - `let r1 = &v; let r2 = &v; // each has view of v's data`
- Mutable Vec, non-mutable references – creating reference inhibits Vec mutation:
  - `let mut v = vec![1,2,3];`
  - `let r1 = &v; let r2 = &v; // each has view of v's data`
  - `r1` and `r2` borrow `v`'s data ownership // `v` cannot mutate while borrows are active
  - Borrows end when they go out of scope or are dropped, `drop(r1);`
- Mutable data, mutable reference – writer `v`'s ability to write borrowed
  - `let mut v = vec![1,2,3];`
  - `let mut r = &v; // r has exclusively borrowed v's ownership`
  - `v` cannot mutate until borrow ends



# Rust won't allow mutation with an active reference

```
File Edit Selection View Go Run Terminal Help
main.rs - type_safety - Visual Studio Code

EXPLORER
OPEN EDITORS
  X main.rs src 1, U
TYPE SAFETY
  src
    main.rs 1, U
  target
  .gitignore U
  Cargo.lock U
  Cargo.toml U
  OUTLINE

main.rs
src > main.rs > ...
1 fn main() {
2     let mut v = Vec::<i32>::with_capacity(3);
3     v.push(1);
4     v.push(2);
5     v.push(3);
6     print!("\n v capacity = {}", v.capacity());
7
8     let r1 = &v[1];
9     print!("\n address of v[1] = {:?}" , &v[1] as *const i32);
10    print!("\n address of r1  = {:?}" , r1 as *const i32);
11
12    v.push(4); // fails to compile, can't mutate while borrowed
13    print!("\n address of v[1] = {:?}" , &v[1] as *const i32);
14    print!("\n address of r1  = {:?}" , r1 as *const i32);
15
16    println!("\n\n Hello, Ownership!\n");
17 }
18

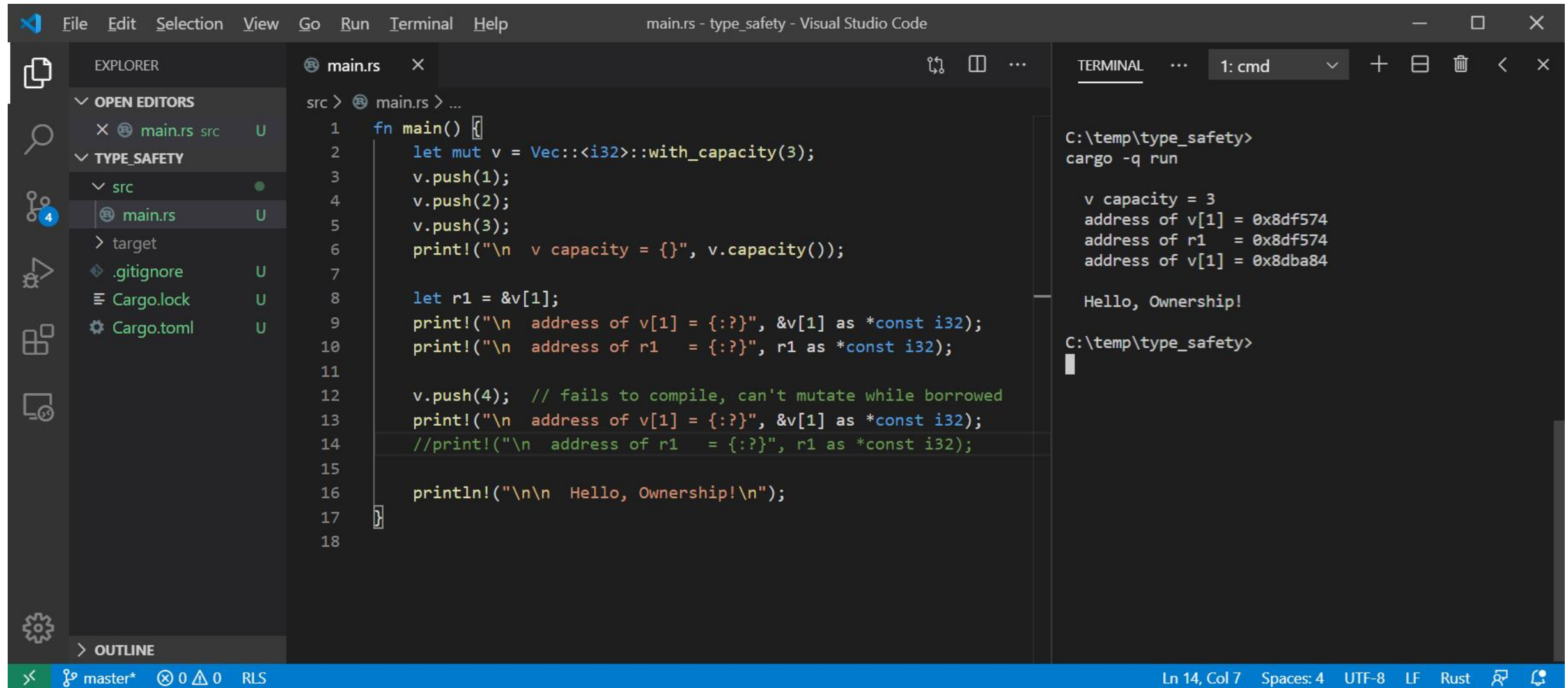
TERMINAL
1: cmd
- immutable borrow occurs here
...
12 |     v.push(4); // fails to compile, can't m
    |               utate while borrowed
    |               ^^^^^^^^^ mutable borrow occurs here
13 |     print!("\n address of v[1] = {:?}", &v[
    |                                           1] as *const i32);
14 |     print!("\n address of r1  = {:?}", r1
    |                                           as *const i32);
    |                                           --
    |                                           immutable borrow later used here

error: aborting due to previous error

For more information about this error, try `rustc --explain E0502`.
error: could not compile `type_safety`.

To learn more, run the command again with --verbose.
C:\temp\type_safety>
```

# Rust allows mutation if we don't use the reference



```
File Edit Selection View Go Run Terminal Help main.rs - type_safety - Visual Studio Code

EXPLORER
OPEN EDITORS
  main.rs src U
TYPE SAFETY
  src
    main.rs U
  target
    .gitignore U
    Cargo.lock U
    Cargo.toml U
  OUTLINE

main.rs
src > main.rs > ...
1 fn main() {
2     let mut v = Vec::<i32>::with_capacity(3);
3     v.push(1);
4     v.push(2);
5     v.push(3);
6     println!("\n v capacity = {}", v.capacity());
7
8     let r1 = &v[1];
9     println!("\n address of v[1] = {:?}" , &v[1] as *const i32);
10    println!("\n address of r1   = {:?}" , r1 as *const i32);
11
12    v.push(4); // fails to compile, can't mutate while borrowed
13    println!("\n address of v[1] = {:?}" , &v[1] as *const i32);
14    //println!("\n address of r1   = {:?}" , r1 as *const i32);
15
16    println!("\n\n Hello, Ownership!\n");
17
18 }
```

TERMINAL 1: cmd

```
C:\temp\type_safety> cargo -q run

v capacity = 3
address of v[1] = 0x8df574
address of r1   = 0x8df574
address of v[1] = 0x8dba84

Hello, Ownership!

C:\temp\type_safety>
```

Ln 14, Col 7 Spaces: 4 UTF-8 LF Rust

# Immutable References

- Any number of immutable references may be declared for a value:
  - `let mut s = String::from("a string");`
  - `let r1 = &s;`
  - `let r2 = &s;`
- The original owner can not mutate until all active references are dropped or go out of scope:
  - `fn show(s:&String) { ... }`
  - `let mut t = String::from("another string");`
  - `show(&t);`
  - `t.push_str(" with more stuff");`  
`// mutation ok, left &t's scope, e.g. show function exit`

# Mutable References

- Only one mutable reference may be declared for a value:
  - `let mut s = String::from("a string");`
  - `let mut r1: &String = &s;`
  - `// let mut r2: &String = &s; // won't compile`
  - `// let r3 = &s; // won't compile`
- The original owner can not mutate until active reference is dropped or goes out of scope (same as before):
  - `fn show(s:&String) { ... }`
  - `let mut t = String::from("another string");`
  - `show(&t); // copies reference to show stack frame, e.g., a borrow`
  - `t.push_str(" with more stuff");`  
`// mutation ok, &mut t went out of scope`

# Ownership summary

- These simple rules provide memory safety:
  - `let x = y`  $\Rightarrow$  copy if blittable, otherwise move  $\Rightarrow$  transfer of ownership
  - Can't use y if moved from
  - `let r1 = &x; let r2 = &x;`  
 $\Rightarrow$  may have any number of immutable references
  - x may not be mutated while there are active references
  - `let mut z = ...`
  - `let mut r3 = &z;`  $\Rightarrow$  may only have one mutable reference
- References become inactive when they go out of scope or are dropped:
  - `drop(r3);`
- Prefer use of references for pass by reference functions and methods

# Rust Object Model

- Rust does not have classes but structs are used in a way very similar to the way classes are used in C++.
- Structs have:
  - Composed members, may be instances of language or user defined types.
  - Aggregated members, using the `Box<T>` construct:
    - `Box<T>` acts like a `std::unique_ptr<T>` in C++.
  - Methods - functions that accept `&self` which is a reference to the instance invoking the function.
    - `&self` is similar to the C++ pointer `this`.
  - Traits - implemented by a struct, similar to Java or C# interfaces.
  - Access control - uses the keyword `pub`.
    - Anything not decorated with `pub` is private but accessible in the local crate.

# Traits

- Traits provide a contract – function specifications – that guarantee behavior.
  - Any type that implements the Clone trait can be cloned by calling `clone()`.
- Functions can accept arguments specified with either types or traits.
  - Specifying arguments with traits is more powerful – and more expensive.
  - Function will process any argument with a specified trait regardless of their type.
- If a type implements a trait, the trait methods become part of the public interface for that type, e.g., methods that can be called.
- You can even implement traits on existing types, much like C# extension methods.

# Common Traits

- Derivable Traits
  - `#[derive(Debug)]`
  - `Debug`, `Display`, `Copy`, `Clone`
  - `PartialEq`, `Eq`, `PartialOrd`, `Ord`
  - `Hash`, `Default`
- Common Rust Traits
  - `ToString`, `From`, `Into`
  - `AsRef`, `DeRef`
  - `Iterator`
  - `Read`, `Write`
- <https://stevedonovan.github.io/rustifications/2018/09/08/common-rust-traits.html>
- <https://stevedonovan.github.io/rust-gentle-intro/>



# Implementing Traits and Methods

```
• trait Size {  
    fn size(&self) -> usize;  
}  
  
• trait Show : Debug {  
    fn show(&self) {  
        print!("\n {:?}", &self);  
    }  
}  
  
• #[derive(Debug, Copy, Clone)]  
pub struct Test { x:i32, y:f64, }  
  
• impl Size for Test {  
    fn size(&self) -> usize {  
        std::mem::size_of::<Test>()  
    }  
}
```

```
• impl Show for Test {}  
  // using default impl  
  
• impl Test {  
    pub fn new() -> Self {  
        Self { x:42, y:1.5, }  
    }  
    ...  
}
```

# Rust Object Model – Static Binding

- `trait Show : Debug { ... }`
- `trait Size { ... }`
- `struct Test { x:i32, y:f64, }`
- `impl Show for Test { ... }`
- `impl Size for Test { ... }`
- `impl Test { ... }`

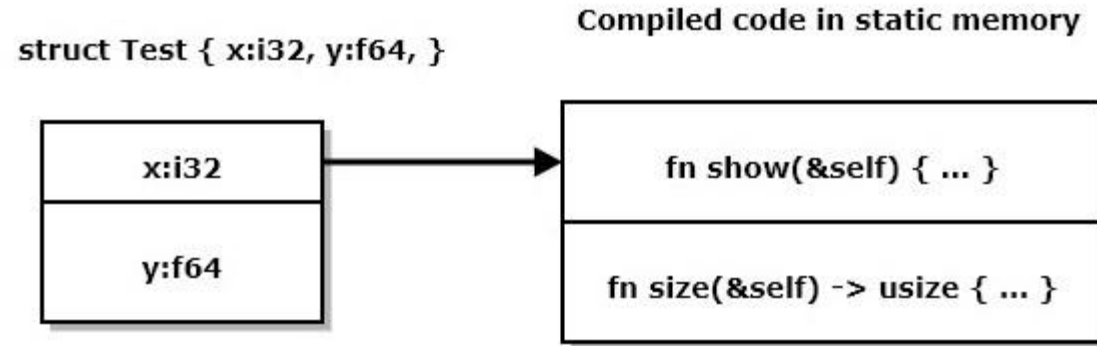
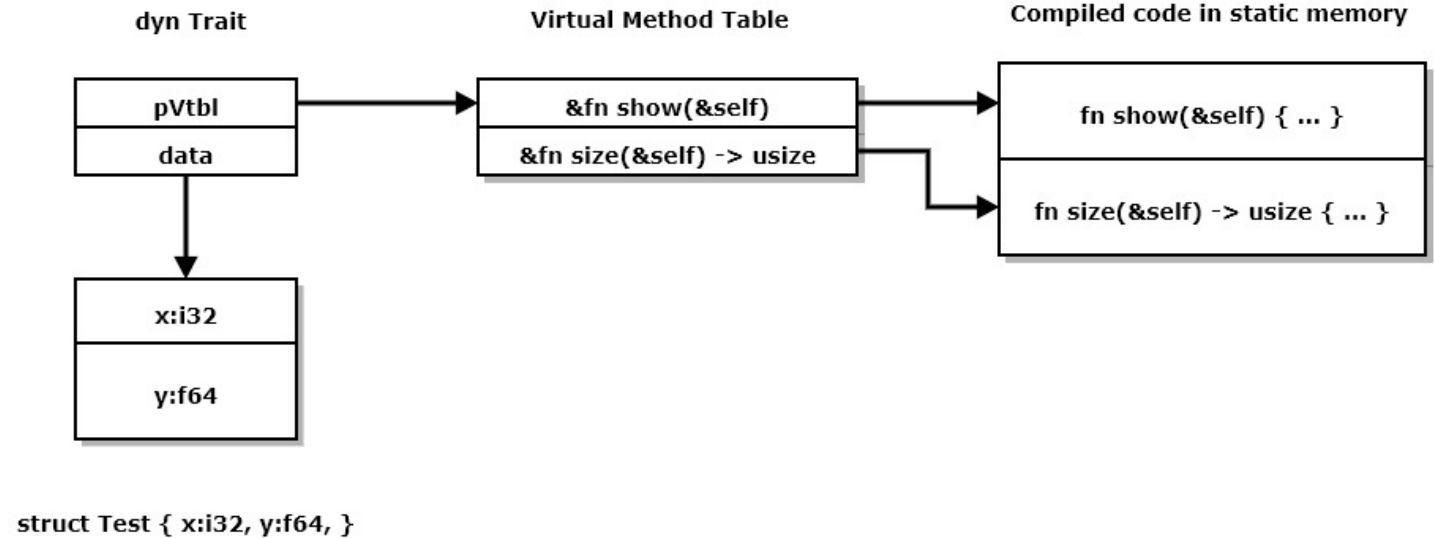


Table 1. Test Struct Memory Layout		
Component	Address	Size - bytes
Test Struct	8190584	16
y:f64	8190584	8
x:i32	8190592	4
padding	8190596	4

# Rust Object Model – Dynamic Binding

- `trait Show : Debug { ... }`
- `trait Size { ... }`
- `struct Test { x:i32, y:f64, }`
- `impl Show for Test { ... }`
- `impl Size for Test { ... }`
- `impl Test { ... }`



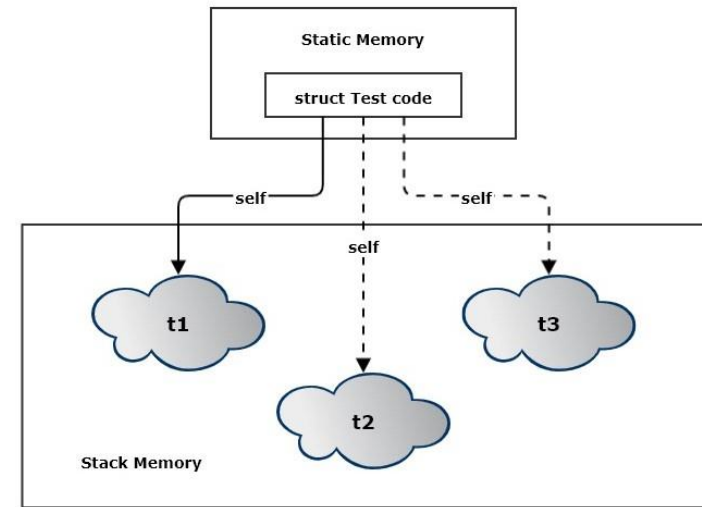
- `fn size_is(o:&dyn Size) ->usize {  
    o.size()  
}`

`size_is(...)` doesn't know anything about `Test`. It does know `Size::size`

- `let mut t = Test { x:42, y:1.5, };  
print!(  
    "size of t = {:?}" , size_is(&t)  
);`

# Copy and Move Types

- Copy types have **instances** that can be copied and assigned.
  - `let t = Test::new();`
  - `let u = t; // copy`
  - `t = u; // assign`
  - Value types implement Copy and Clone traits
- Move types have instances that are moved instead of copied. Any type that does not implement Copy is a move type.
- Moveable types can implement the Clone trait but not Copy.
- Test is a value type.



```
• trait Size {  
    fn size(&self) -> usize;  
}  
• trait Show : Debug {  
    fn show(&self) {  
        print!("\n {:?}", &self);  
    }  
}  
• #[derive(Debug, Copy, Clone)]  
  pub struct Test { x:i32, y:f64, }  
• impl Size for Test {  
    fn size(&self) -> usize {  
        std::mem::size_of::<Test>()  
    }  
}
```

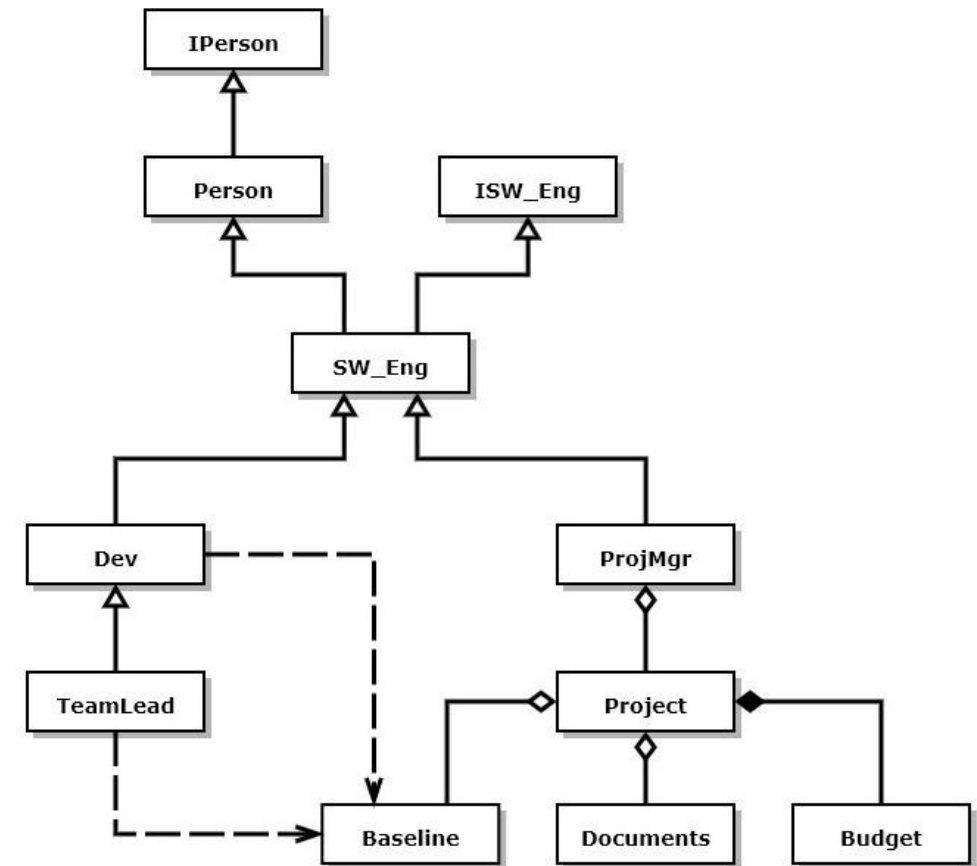
```
• impl Show for Test {}  
  // using default impl  
• impl Test {  
    pub fn new() -> Self {  
        Self { x:42, y:1.5, }  
    }  
}
```

# Comparison with C++

- C++ object model provides:
  - Composition
  - Aggregation
  - Inheritance
- Most classes can be value types:
  - Copy constructors
  - Assignment operator overloads
  - Destructors
- Many are value types by default
  - Members are primitive types or STL containers
- Rust object model provides:
  - Composition
  - Aggregation
  - Traits
    - Provide functions but no data
- Some structs are Copy, but many must be Move.
  - No overloads, so no overloaded assignment operators
  - Move types can implement clone() but that is never called implicitly

# C++ Person Class Hierarchy Example – from C++ Models

- The class structure shown on the right represents a software development organization.
- Software Engineers inherit the person type and implement the ISW\_Eng interface. SW\_Eng is an abstract base class for all software engineers.
- Any function that accepts a pointer to SW\_Eng will also accept pointers to Devs, TeamLeads, and ProjMgrs.
- If ISW\_Eng defines a pure virtual method, say doWork(), any derived class can override that method.
  - Devs doWork that devs do
  - TeamLeads doWork that team leads do
  - ProjMgrs doWork that project managers do
- So the doWork() method binds to code based on the type of object bound to an ISW\_Eng pointer.



# Rust Generics

- Rust Generics define trait constraints that limit the types that will compile.
- Rust generics do not support specializations that broaden the number of types that can be used.

- Generic functions:

- ```
fn demo_ref<T>(t:&T) where T:Debug {  
    show_type(t);  
    show_value(t);  
}
```
- ```
fn show_type<T: Debug>(_value:&T) {  
    let name = std::any::type_name::<T>();  
    print!(  
        "\n  TypeId: {:?}, size: {:?}",  
        name, size_of::<T>()  
    )  
}
```

- Generic structs:

- ```
#[derive(Debug)]  
struct Point<T> { x:T, y:T, z:T }
```

# Traits

- Traits provide a contract – function specifications – that guarantee behavior.
  - Any type that implements the Clone trait can be cloned by calling `clone()`.
- Functions can accept arguments specified with either types or traits.
  - Specifying arguments with traits is more powerful – and more expensive.
  - Function will process any argument with a specified trait regardless of their type.
- If a type implements a trait, the trait methods become part of the public interface for that type, e.g., methods that can be called.
- You can even implement traits on existing types, much like C# extension methods.



# Traits – Note: these traits don't use T, but their implementation does

- ```
trait Show : Debug {  
    fn show(&self) {  
        print!("\n {:?}", &self);  
    }  
}
```
- ```
trait Size {  
    fn size(&self) -> usize;  
}
```
- ```
fn size_is(o:&dyn Size) ->usize {  
    o.size()  
}
```

size\_is(o:&dyn Size) accepts both ordinary and generic arguments
- ```
#[derive(Debug, Copy, Clone)]  
pub struct Point<T>{ // public type  
    x:T, y:T, z:T,    // private data  
}
```

- ```
impl<T> Show for Point<T>  
    where T:Debug {} // using default impl
```
- ```
impl<T> Size for Point<T> {  
    // must provide impl  
    fn size(&self) -> usize {  
        std::mem::size_of::<Point<T>>()  
    }  
}
```
- ```
let mut t =  
    Point { x:0.0, y:1.0, z:0.5, };
```
- ```
t.show();
```
- ```
print!(  
    "\n size of t = {:?}", size_is(&t)  
);
```

# Generics Summary

- Generics help us build flexible code:
  - Create collections that can hold many different types, but we need only one design.
- Generics with traits provide even more help
  - Define functions and methods that accept arguments that satisfy a trait specification.
  - Much more flexible than defining functions that take specific typed arguments.
  - Allows us to specify that only some categories of types should be accepted, e.g., move-able, or clone-able, or display-able.

# Code Structure

- Source code is written in files
- For many software systems file structures become large and hard to understand.
- To support readability and maintenance, we create packages that consist of a few files with a single purpose and document the purpose and design in comments.
  - Source files are units of construction
    - Binaries - /src/main.rs – has main function, builds to an executable
    - Libraries - /src/lib.rs – builds to library
    - Modules - /src/\*.rs – loaded when building binaries and libraries
  - A Crate is a unit of translation
  - Crates start as a set of source files in the /src directory and compile to a single file:
    - Binaries - /target/debug/[package\_name].exe on windows
    - Libraries - /target/debug/lib[package\_name].rlib

# Crate

- The source form of a crate is composed of:
  - A crate root, `main.rs` or `lib.rs`, and a set of zero or more supporting source files called modules, all found in the `/src` folder.
  - The crate root loads any modules identified with the keyword `mod` at the top of its source.
    - `mod some_module` → loads `some_module.rs`
  - Each module may also load other modules.
  - The crate may specify dependencies on other crates and import their definitions into the root or any of its modules.
    - Dependencies are specified in the `[dependencies]` section of the `cargo.toml` file.
- The translation form of a crate is a single compiled file, e.g., one of:
  - `/target/debug/[package_name].exe`
  - `/target/debug/lib[package_name].rlib`

# External Dependencies

- External dependencies may be local or remote:

In cargo.toml:

```
[package]
name = "test_rust"
version = "0.1.0"
authors = ["James W. Fawcett <jfawcett@twcnny.rr.com>"]
edition = "2018"

[dependencies]
my_lib = { path = "../my_lib" } // from local drive
serde = "1.0.104" // from https://crates.io
```

- The cargo build process will load my\_lib and serde crates before building this crate.

# Packages

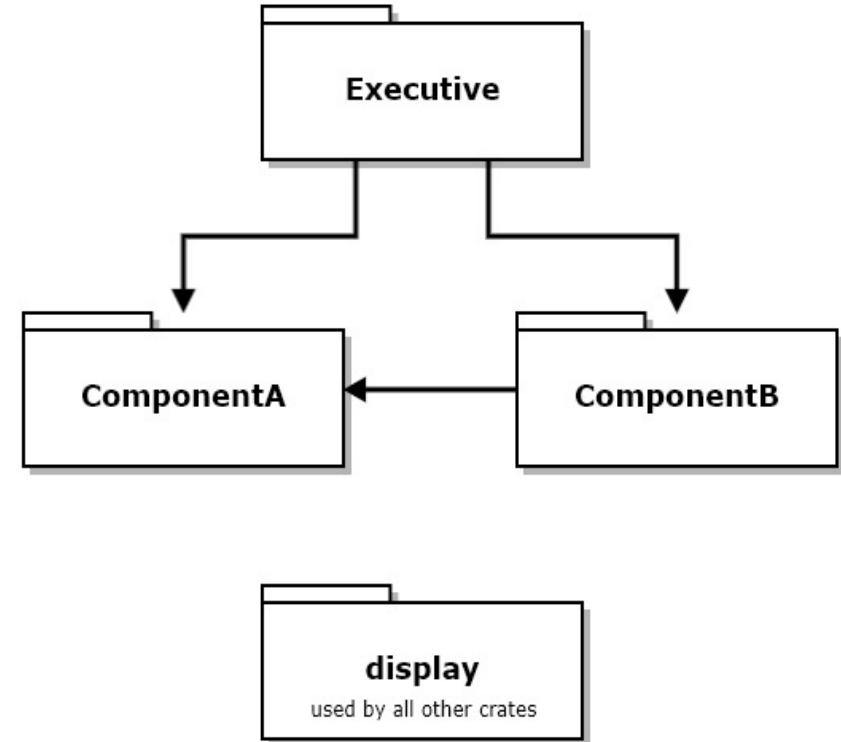
- A Package is a collection of directories and files that are the basis for builds
  - Cargo.toml – specifies package metadata, dependencies, and optional directives
  - /src – directory containing a binary or library source crate
  - /target – directory containing translated binaries or libraries
  - /examples – directory containing example code that exercises the package library
- The Rust build system is transitive
  - Builds start with the package root cargo.toml
  - Parse it to find dependencies
  - Load the depending library and parse its cargo.toml
  - ...
  - Build the local crate along with its dependencies

# Library Crate Construction Co-Tests

- For anything other than trivial example code it's very useful to test as we build code:
  - A library crate is created with the command **cargo new --lib [package-name]**.
  - That builds a lib.rs containing a single configured test that asserts  $2 + 2 = 4$ .
    - This is simply a demonstration of how to build test cases for a library.
    - Each test passes if, and only if, there are no failed assertions.
  - Every time we add a few lines of code in the lib.rs file we add small tests, each in a configured test block and then build and execute with the command:  
**cargo test**  
in a terminal window located in the crate root folder.
  - This “co-test” process allows us to very quickly find errors. If a test fails, the problem is almost certain to be in the few lines of code we entered after the last test.

# Example – Crates and Packages

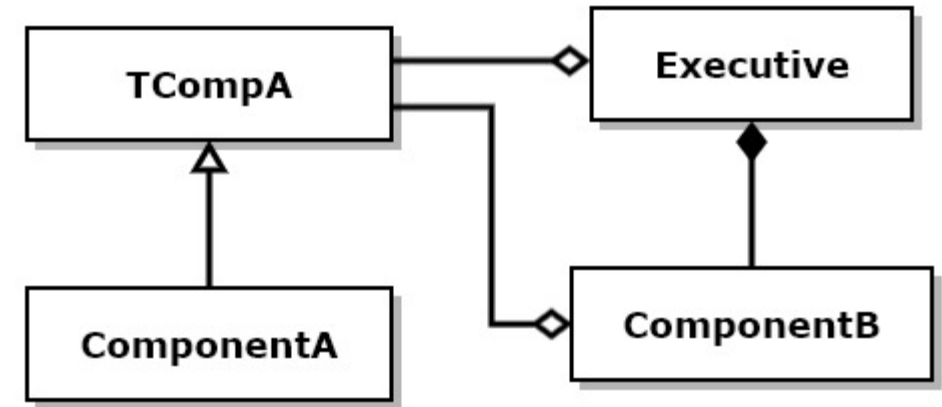
- The diagram at the right shows a set of crates that work together to implement some functionality.
- The diagram shows dependency relationships between crates.
- The ComponentA crate provides an interface and object factory to allow ComponentB and Executive to use it without binding to its implementation details.
- The Executive package consists of all three of these crates.
- Code for this example:  
<https://github.com/JimFawcett/RustBasicDemos/> in code\_structure\_demo





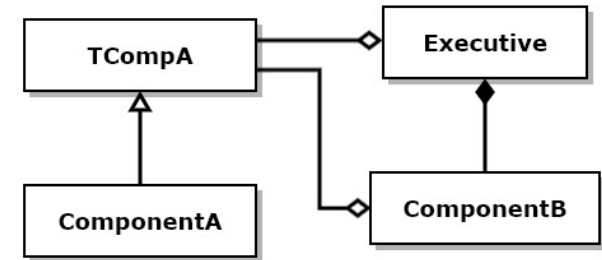
# Example – Traits and Structs

- This diagram shows structs that are defined in each of the files from the previous slide.
  - TCompA is an interface<sup>1</sup> trait for ComponentA
  - ComponentA implements the trait to provide exported services
  - ComponentB doesn't provide an interface
  - ComponentB uses ComponentA through its interface trait and factory<sup>2</sup>
  - Executive composes ComponentB and uses ComponentA through its trait and factory



- 
1. Rust does not have an interface construct. We use traits with virtual functions for that purpose.
  2. ComponentA's factory is implemented with a function, declared and implemented in ComponentA.

# Use of Interfaces and Factories



- If you look at interface trait TCompA you will see it has no implementation detail.

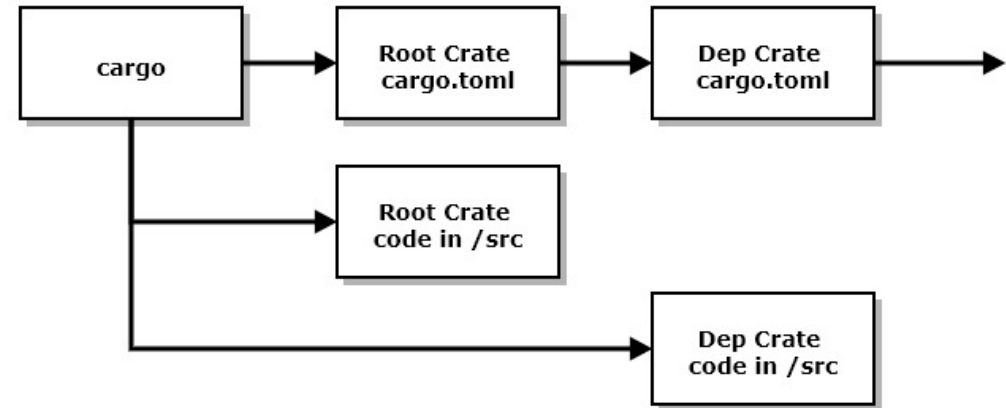
```
pub Trait TCompA {  
    fn do_work(&self);  
    fn get_msg(&self) -> String;  
    fn set_msg(&mut self, m:&str);  
}
```

```
pub fn get_instance() -> Box<dyn TCompA> {  
    Box::new(ComponentA::new())  
}
```

- Executive and ComponentB use ComponentA's factory function, get\_instance to avoid binding to the concrete ComponentA type.
- That means that Executive and ComponentB have no source dependencies on ComponentA. ComponentA can change any of its implementation without affecting Executive or ComponentB as long as the interface, TCompA, and factory function signature, get\_instance, don't change.

# Compilation Model

- Rust compilation is a transitive depth first search process.
- The cargo build tool starts by parsing the package's cargo.toml file, looking for dependencies and build attribute specifications.
- For each dependency cargo parses its dependencies transitively until it reaches a cargo.toml with no dependencies.
- It then builds that crate root with its loaded modules, then returns to the previous crate in the dependency tree.
- When it returns to the build package it builds the files in /src and deposits its results in /target.
- If any of the dependencies have current builds, that library in /target is used and files in /src are not built.

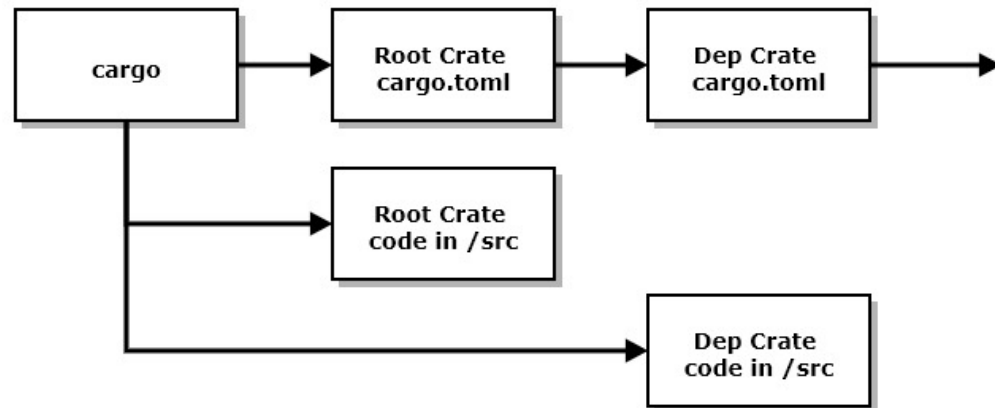


- Note that cargo.toml files may list zero or more dependencies, so the dependency structure is a tree, not a list.

# Cargo Builds

## Compilation of external libraries

- Cargo.toml lists dependencies on external libraries. These are loaded and built or retrieved from the build cache.
- This is a transitive process, that walks the crate's dependency tree.



## Compilation of local sources

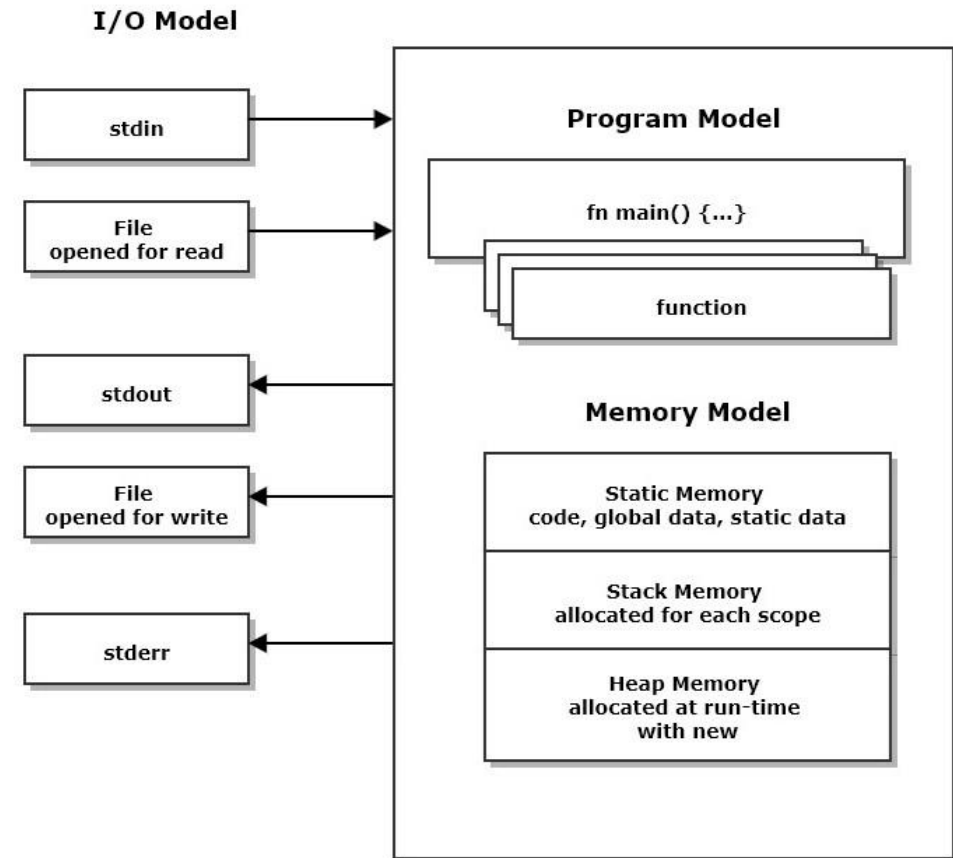
- When external library dependencies are resolved cargo builds:
  - The crate root in /src, main.rs or lib.rs
  - Any modules that the crate root depends on – they reside in the same /src directory.
- Cargo knows about these module dependencies:
  - The crate root file declares modules it depends on with a `mod file_name` declaration.
  - Modules may declare dependencies on other modules in the same way.

# Program Execution

- There are three ways to execute code in a fully formed crate, using cargo:
  - Execution of binaries:  
If the crate root is a binary, e.g., main.rs, the command  
**cargo run**  
will execute the program
  - Testing libraries:  
If the crate root is a library, e.g., lib.rs, the command  
**cargo test**  
will run any tests configured at the end of the library. Tests pass if there are no assertions in the test code, and fail if there are.
  - Running examples:  
For library crates, if you create an /examples folder and put demonstration modules there, then the command  
**cargo run --example an\_example**  
will run the code in an\_example.rs, assuming that you've supplied a main function for that module. The user expects that this code will demonstrate use of library functionality.

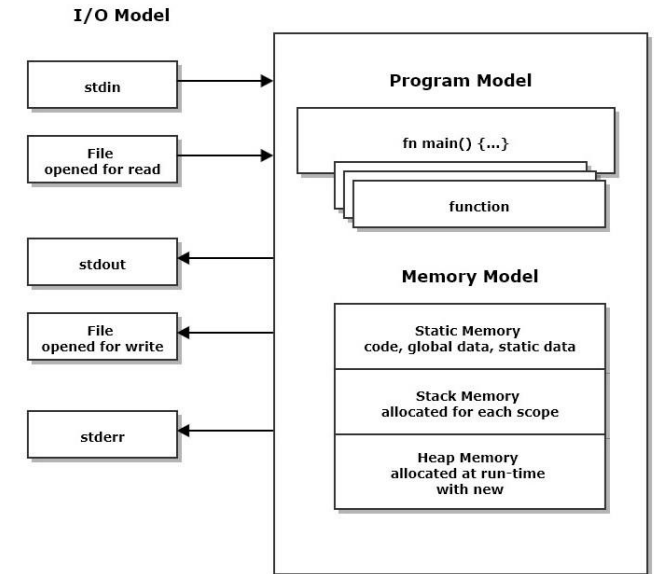
# Program Execution

- When the executable for a program is loaded:
  - Initialization code provided by the compiler executes
  - Then the function main is entered.
    - main is just a function that is defined to the linker as the entry point for processing.
- Any function may call other functions within the executable.



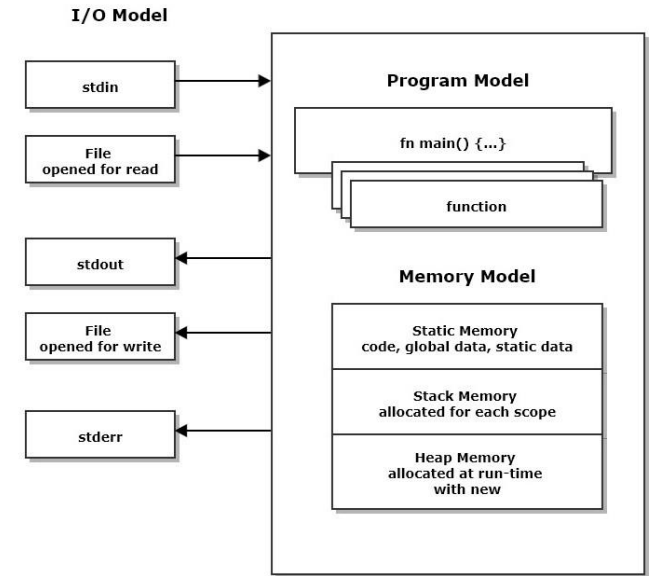
# Use of program memory

- When the thread of execution enters a function an allocation of stack memory is used to store function parameters and any local data defined in the function.
  - The same thing happens for every scope, defined by a matching pair of braces, { and }. For example, an if statement, using braces, allocates stack memory to hold data local to its scope.
- A program may place any of its entities, e.g., an instance of a user-defined type, into static memory, stack memory, or heap memory.
- We will discuss consequences of that later in the next slide.



# Interaction with the Execution Environment

- There are two primary ways for a Rust program to observe and use its execution environment:
  - Use a stream object like `std::stdin` or `std::stdout`.
  - Types for streams are provided by the standard library, via import statements:  
use `std::io::prelude::*`, use `std::fs::File`, ...
- The program may use services of its platform API by using `std::ffi` (Foreign Function Interface) in an `unsafe` block or by using a crate that wraps that:
  - <https://github.com/retep998/winapi-rs>





# Rust Pain Points

- Ownership
  - Conceptually simple, must handle details to compile 😞
  - Compiler error messages are very good 😊
- Error Handling
  - All cases of all errors have to be handled to compile
  - Many examples use naïve handling, e.g., panic.
    - Not a good idea for anything other than demo code.
- Strings
  - String, &str, OsString, &OsStr, PathBuf, &Path
  - No indexing, can use iterator
- Explicit conversions
  - Virtually no implicit conversions

# Epilog

[https://jimfawcett.github.io/RustStory\\_Prologue.html](https://jimfawcett.github.io/RustStory_Prologue.html)

# Conclusions

- If you understand the models, we've covered, I think you will find Rust syntax and semantics to be convenient and sensible.
- Some particular parts of the language discussed in the Rust Story but not here are intricate and require some study to master:
  - String syntax and semantics because the only character type Rust recognizes in its native strings, `String` and `Str`, is utf-8, which uses multi-byte characters of varying sizes.
  - Life-time annotation needed for some scenarios using generics.
  - Many crates in <https://crates.io> are used routinely by knowledgeable Rust developers, but some take significant amounts of time and effort to use effectively.
- Rust avoids undefined behavior by incorporating a safe type system. That is based on the ownership rules we've discussed. It takes a while to get use to the rules, but compiler error messages are usually very good.

# Presentation Resources

- The ideas discussed in this presentation are drawn from a web page:  
[https://jimfawcett.github.io/RustStory\\_Models.html](https://jimfawcett.github.io/RustStory_Models.html)

which is part of the Rust Story:

[https://jimfawcett.github.io/RustStory\\_Prologue.html](https://jimfawcett.github.io/RustStory_Prologue.html)

- And code examples for the story are documented here:  
<https://jimfawcett.github.io/RustStoryRepo.html>

- These slides are available here:  
<https://jimfawcett.github.io/Resources/RustTour.pdf>

# Background

- The material for this presentation comes from the github website:
  - <https://JimFawcett.github.io>,  
<https://jimfawcett.github.io/Resources/RustModels.pdf>
- The site provides a curated selection of code developed for graduate software design courses at Syracuse University
- It also contains tutorial and reference materials related to that code.
- Some of that is presented in the form of “stories”
- Rust Models is the title of the first chapter of a “[Rust Story](#)”
  - The story is a detailed walk-through of the Rust programming language. It provides reference material for a set of [repositories](#) that hold source code for utilities, tools, components, and demonstrations.