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Rust: A Richly Typed, Memory-safe, Algebraic Systems Language for Writing Perfect Code

Started as a passion project at Mozilla in 2006, Rust has infiltrated the market as a new, production ready, paradigm shifting language. The Rust team's devotion to safety and speed has allowed them to reach their three goals: performance, reliability, and productivity (*Rustteam*).

Rust has several features that make it unique. Rust achieves memory safety without a garbage collector. Rust programmers enjoy high level ergonomics with low level control and speed. Rust's rich and algebraic type system achieves type safety while weeding out numerous errors at compile time. Rust has been voted the most loved programming language 7 years in a row. (*Overflow*) Rust's applications span from as low as embedded devices to as high as SSR Web Assembly. "The last 40 years was written in C, the next 40 will be written in Rust" (*Oatman*).

Rust approaches memory management with a new paradigm. It uses neither a garbage collector nor forces memory management on the programmer; instead it achieves memory safety using a borrow checker. The borrow checker has two rules: data has one owner and data may have multiple readers or one writer. When a piece of non-global data is instantiated, a sized portion of data from the stack, or a chunk of data in the heap, is allocated to it. The variable that the data is assigned to is its owner. Passing data by value (IE not through a pointer) moves the data to the function it was passed into. This data is

gone, it can neither be accessed nor modified by the previous owner. In order to share data without moving, pass a reference (pointer) to the data. Passing a variable through a reference is called borrowing.

In order to understand how the borrow checker functions, one must understand variable lifetimes and scope. When the owner of a value goes out of scope, the value is dropped. A variable's scope is defined by the narrowest set of curly braces (this is often called a block). A variable comes into scope when it is declared and exits scope when program execution exits its block. A variable's lifetime is the length of time it is in scope. The lifetime of the owner of a value must exceed the lifetime of all references to it. This lifetime restriction makes null and dangling pointers impossible.

```
fn main() {
    // 's' comes into scope as it is declared
    let s: String = String::from("This is a string");

    // Pass 's' by reference
    // 's' still owns the String
    let len: usize = get_len(&s);

    println!("The length of '{}'' is {}", s, len);
} // This scope is now over and 's' is no longer valid

fn get_len(rs: &String) -> usize { // 'rs' is declared here
    rs.len();
} // 'rs' goes out of scope here and is dropped
```

A mutable reference to a value must be the only reference to that value. This restriction prevents race conditions when reading or modifying data. If another part of the program tries to read or modify a piece of data that is also being modified by a mutable reference, a race condition could occur and inconsistent results would be produced. Rust's imperviousness to race conditions is coined as "Fearless Concurrency".

Rust is a very strongly typed language, meaning that data must have a defined or

inferred type and must conform to stricter compiler rules and safeties. Rust's type system prevents programmers from making common and redundant mistakes at compile time (or more realistically linted in the editor). Every Rust builtin type has several guarantees if it compiles. For example, the *String* type guarantees that it will always be a valid UTF-8 encoded (Unicode) vector of bytes that can be displayed. While it may seem trivial, nearly all systems languages and quite a few higher level languages will allow the programmer to do unsafe or unrepresentable things with strings.

C-style structs allow Rust programmers to create custom data types that improve readability, code structure, and safety. Structs can be thought of as a custom blueprint for a semantically useful datatype. They are type-checked by the compiler and follow a C-style key-value syntax. Structs are private by default and cannot be accessed by other files unless defined with the *pub* keyword.

```
use chrono::{Local, DateTime};
use sha256::digest;

// Define the User struct with several fields
struct User {
    username: String,
    email: String,
    password_hash: String,
    last_logon: DateTime<Local>,
    google_uuid: Option<String>,
}

fn main() {
    // Construct a user object
    let user = User {
        username: String::from("hoehlrich"),
        email: String::from("henry@oehlrich.xyz"),
        password_hash: digest("password123"),
        last_logon: Local::now(),
        google_uuid: None,
    };
    println!("User '{}' with email '{}' last logged on '{}'.",
        user.username,
        user.email,
```

```

        user.last_logon.format("[%Y-%m-%d] [%H:%M:%S]")
    );
    // output:  User 'hoehlrich' with email 'henry@oehlrich.xyz'
    //          last logged on ' [2023-03-21] [09:25:09] '.
}

```

Unlike other popular languages Rust does not have a higher level of object abstraction above structs. Struct *impl* (implementation) blocks are Rust's form of object oriented methods. Everything in the *impl* block will be associated with the attached struct. Functions defined in implementation blocks that operate on objects are called methods. Methods may take any form or reference of *self* as the first parameter; *self* is the object instance that the method is begin called on.

Enums, or enumerations, allow the programmer to define a type that can be one of a set of values. An enum of colors might include red, blue, yellow, etc; an instance of the colors enum might be red. Enumerations allow a single type to have multiple variants. Enum variations are syntactically demonstrated with the double colon namespacing after the identifier. Functions that take an enum can take any variant of that type. Enum variants are also able to hold data.

```

// Define the Event enum
enum Event {
    LeftClick(i32, i32),    // LeftClick has x and y pos
    RightClick(i32, i32),   // RightClick has x and y pos
    KeyPress(char),         // Key press stores the key pressed
    Quit,                   // Quit does not need to store data
}

fn main() {
    let k_key = KesPress('k');
}

```

In order to add different functionality to different variants of enums, Rust allows the programmer to match patterns on enums. Rust pattern matching is similar to the C or Java switch statement. (*Kernighan and Ritchie*). It is much safer than either of these languages implementations, though; in Rust, the programmer must handle each and every

possible control flow path when matching on enums (even if the handling crashes the program, it must be explicitly stated). Pattern matching can extract and handle the data that may (or may not) be held in an enum instance.

Rust has no nulls. In order to represent the value of none, Rust uses the *Option* enum. The *Option* enum is defined in the standard library. *Option* is either a value *Some(v)*, or *None*. Functions that may or may not return a value should return that value (or lack thereof) as an *Option*. The calling portion of the function can then match on that enum, storing the data if it is valid or proceeding as necessary if the data doesn't exist.

```
// Print google_uuid if it exists, if not give a message
// Remember from a previous example that google_uuid is an Option<String>
match user.google_uuid {
    Some(v) => println!("google uuid: {}", v),
    None => println!("user does not have a google uuid"),
}
```

Perhaps the most useful and paradigm shifting enum is the standard library's *Result* enum. The *Result* type is Rust's answer to error handling. It can either hold a value (*Ok(v)*), or an error (*Err(e)*). In order to access the value (or error) contained in the *Result*, it must be explicitly handled with a match statement or a temporary call to *unwrap*. Errors in results do not interrupt the program control flow as is done with other popular languages; instead, idiomatic Rust programs will propagate any errors up the stack to be dealt with.

A common pattern with *Result* types is to match on the wrapped type assigning the value to a variable and returning the error if it exists. This pattern is so common that the Rust Team assigned it to the *?* operator. At compile time, any uses of *?* will be automatically expanded to the long-form match statements; this is similar, but not the same, as macro expansions.

```
fn read_data() -> Result<String, Box<dyn Error>> {
    // Expanded version of error handling
    let data = match fs::read_to_string("file.txt") {
        Ok(v) => v,
```

```

    Err(e) => return Err(Box::new(e)),
};

// This is the same as above
let data_ = fs::read_to_string("file.txt"?);

// Return the data if there hasn't been an error
return Ok(data);
}

```

Generics in Rust are placeholders for concrete types. The previously discussed enums *Option* and *Result* are both generics. Using generics allows functions, methods, structs, and enums to take multiple possible types without code duplication. Each generic type (specified in angle brackets after the function or struct name) is represented by a letter (commonly T and U). Generic identifiers may be reused in order to specify that two parameters/attributes share the same type. Similarly to the `?` operator, generics do not decrease code performance. In the monomorphization step of compilation, the compiler expands all generics into variants required by the code.

```

fn main() {
    // p1 is defined with coords as two i32s
    let p1 = Point { x: 1, y: 2 };
    // p2 is defined with coords as two f32s
    let p2 = Point { x: 0.34, y: 123.21 };
}

// Struct Point is defined with two attributes of generic type T
struct Point<T> {
    x: T,
    y: T,
}

```

Traits define behavior that can be implemented on multiple types (they are similar to interfaces in other popular languages.) A trait includes a set of function signatures that all types that implement the trait must also implement. Traits can include default implementations that are injected into types that implement the trait but do not override the default function by reimplementing it.

```
// Every type that implements HasSize must implement the associated methods
trait HasSize {
    fn get_len(&self) -> usize;

    fn allocated_size(&self) -> usize;
}

struct Sentence {
    text: String,
    author: String,
}

impl HasSize for Sentence {
    fn get_len(&self) -> usize {
        return self.text.len();
    }

    fn allocated_size(&self) -> usize {
        return self.text.capacity();
    }
}

fn main() {
    let sentence = Sentence {
        text: String::from("Almost done with the rough draft"),
        author: String::from("Henry Oehlrich"),
    };

    println!(
        "Sentence with len {} and allocated size {}",
        sentence.get_len(),
        sentence.allocated_size(),
    )
}
```

Trait bounds allow the programmer to specify the limits or bounds to generic types. In the context of functions, the programmer can specify trait bounds on types by assigning traits to a generic type and then use the resulting generic to specify the type of parameters. This generic form of parameter types allows for functions to take any type that meets the specified requirements.

Because each generic type must have its own trait bounds, function signatures can get

cluttered when multiple generics are involved. Rust has the *where* clause sugar syntax in order to combat this problem. The *where* clause adds trait bounds on previously declared generic types. In cases where a generic is only used once, Rust allows for the standard type annotation to contain an *impl trait* portion.

```
// Add the lengths of two sized lengthfull objects
// Notice the generic declared in the signature
fn add_lens<T: Sized + ExactSizeIterator>(size1: &T, size2: &T) -> usize {
    size1.len() + size2.len()
}

// Print person's info in a generic way
// Generics declared using the where clause
fn print_info<T, U>(name: &T, age: &U)
where
    T: std::fmt::Display,
    U: num::Integer + std::fmt::Display,
{
    println!("{}", name, age);
}
```

Despite all of the unique features of Rust, it still compiles down to raw binary. Types don't exist at the kernel level, all it understands are 1's 0's and a few syscalls. Rust abstractions have no effect on code performance, this quality is coined as "Zero-cost abstractions". Zero-cost abstractions break the common stigma among programming languages: speed and developer ergonomics are mutually exclusive. Instead of trading speed for ergonomics (or vice versa), Rust takes on a steeper initial learning curve and a large amount of syntax for both speed and ergonomics.

During a time of rapid development and advancement, Rust offers a framework for developing fast, safe, and consistent code. The Rust team's devotion to its values has created a strong and loyal userbase devoted to speed, safety, and correctness.

Annotated Bibliography

Kernighan, Bryan, and Dennis Ritchie. *The C Programming Language*. Prentice Hall, 1972.

In this book, the authors, having created the C programming language, give a deep dive into it. This book teaches the reader C, but more importantly, it teaches how computer registers, memory, and data work and are stored at the most basic level. Although it follows a different paradigm from Rust, it is impossible to cohesively cover a programming language without paying homage to C.

Oatman, Tris. <https://www.youtube.com/noboilerplate>. 2022.

This Youtube channel is an excellent secondary/tertiary source for concise, complete analysis of the Rust language. While other sources merely gives the facts, this channel shows real-world applications as well as fun independent use cases.

Overflow, Stack. 2022. <https://survey.stackoverflow.co/2022/>.

The Stack Overflow developer survey is a yearly survey of developers to gather and analyze trends. It is a survey of users of Stack Overflow, that is to say programmers. It could be slightly biased because the most experienced and best programmers do not use stack overflow.

Rustteam. Rust Programming Language. 2023. <https://www.rust-lang.org/>.

This is the official Rust Language website. It is created and maintained by the Rust Team (Rust maintainers) as well as many contributions from the community. It mostly serves as a launching point for learning and participating in Rust. As well as maintaining links, this site has a blog for Rust news for update and feature announcements.