301AA - Advanced Programming

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Course pages:
http://pages.di.unipi.it/corradini/Didattica/AP-18/

AP-2018-24: *RUST*

The RUST programming language

- Brief history
- Overview of main concepts
- Avoiding Aliases + Mutable
- Ownership and borrowing
- Traits, generics and inheritance
- (Slides by Haozhong Zhang)

Brief History

- Development started in 2006 by Graydon Hoare at Mozilla.
- Mozilla sponsored RUST since 2009, and announced it in 2010.
- In 2010 shift from the initial compiler in **OCaml** to a self-hosting compiler written in **Rust**, **`rustc`**: it successfully compiled itself in 2011.
- **`rustc`** uses **LLVM** as its back end.
- Most loved programming language in the Stack Overflow annual survey of 2016, 2017 and 2018.

On RUST syntax

- **Rust** is a systems programming language with a focus on safety, especially safe concurrency, supporting both functional and imperative paradigms.
- Concrete syntax similar to C and C++ (blocks, `if-else`, `while`, `for`), `match` for pattern matching
- *Despite the superficial resemblance to C and C++, the syntax of Rust in a deeper sense is closer to that of the ML family of languages as well as the Haskell language.*
- Nearly every part of a function body is an expression (including `if-else`).

Memory safety

- Designed to be memory safe:
  - No null pointers
  - No dangling pointers
  - No data races
- Data values can only be initialized through a fixed set of forms, requiring their inputs to be already initialized. Compile time error if any branch of code fails to assign a value to the variable.
- Rust core library provides an **option type**, which can be used to test if a pointer has Some value or None.
- Rust also introduces syntax to manage **lifetimes**, and the compiler reasons about these through its ***borrow checker***.

Memory management

- No garbage collection. Deterministic management of resources, with very low overhead.
- Memory and other resources managed through Resource Acquisition Is Initialization (**RAII**), with optional reference counting.
- Rust favors stack allocation (default). No implicit boxing.
- Safety in the use of pointers/references/aliases is guaranteed by the **Ownership System** and by the compilation phase of **borrowing checking**.

Ownership System

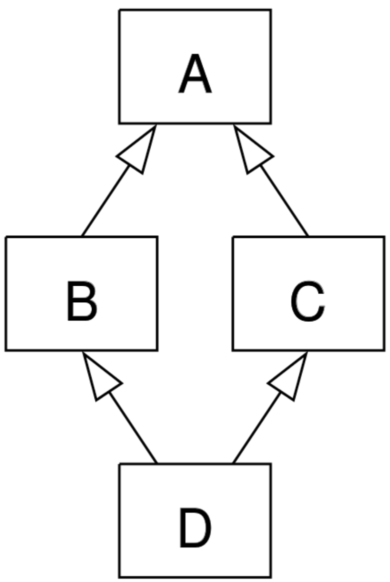
- Rust has an ownership system, based on concepts of ownership, borrowing and lifetimes
- Data are immutable by default, and declared mutable using **`mut`**.
- All values have a unique owner where the scope of the value is the same as the scope of the owner.
- A resource can be borrowed from its owner (via assignment or parameter passing) according to some rules.
- Values can be passed by immutable reference using **`&T`**, by mutable reference using **`&mut T`** or by value using **`T`**.
- At all times, there can either be multiple immutable references or one mutable reference to a resource. This is checked statically.

Types and polymorphism

- **Type inference**, for variables declared with the **let** keyword.
- Classes are defined using **structs** for fields and implementations (**impl**) for methods.
- **No inheritance** in RUST! ➔ Pushing **composition over inheritance**
- The type system supports **traits**, corresponding to Haskell type classes, for ad hoc polymorphism.
- Traits can contain abstract methods or also concrete (default) methods. They cannot declare fields.
- Support for **bounded universal explicit polymorphism** with **generics**, as in Java, where bounds are one or more traits.

Digression: The diamond problem of multiple inheritance

- Two classes B and C inherit from A, and class D inherits from both B and C. If there is a method in A that B and C have overridden, and D does not override it, then which version of the method does D inherit: that of B, or that of C?
- Java 8 introduces default methods on interfaces. If A,B,C are interfaces, B,C can each provide a different implementation to an abstract method of A, causing the diamond problem.
- Either class D must reimplement the method, or the ambiguity will be rejected as a compile error.



Generic functions

- Generic functions may have the generic type of parameter bound by one or more traits. Within such a function, the generic value can only be used through those traits.
- Therefore a generic function can be type-checked when defined (as in Java, unlike C++ templates).
- However, *implementation* of Rust generics similar to typical implementation of C++ templates: a separate copy of the code is generated for each instantiation.
- This is called **monomorphization** and contrasts with the type erasure scheme of Java.
  - Pros: optimized code for each specific use case
  - Conss: increased compile time and size of the resulting binaries.

An Introduction
to
Rust Programming Language

Haozhong Zhang

Jun 1, 2015

Slides freely adapted by the lecturer

As a programming language …

```
fn main() {
    println!(“Hello, world!”);
}
```

- **Rust** is a *system programming language* barely on the *hardware*.
  - No *runtime* requirement (*eg*. GC/Dynamic Type/…)
  - More *control* (*over* memory allocation/destruction/…)
  - …

More than that …

C/C++ Haskell/Python

more control,
less safety

less control,
more safety

Rust

more control,
more safety

Rust overview

Performance, as with C
- Rust compilation to object code for bare-metal performance

But, supports memory safety
- Programs dereference only previously allocated pointers that have not been freed
- Out-of-bound array accesses not allowed

With low overhead
- Compiler checks to make sure rules for memory safety are followed
- Zero-cost abstraction in managing memory (i.e. no garbage collection)

Via
- Advanced type system
- Ownership, borrowing, and lifetime concepts to prevent memory corruption issues

But at a cost
- Cognitive cost to programmers who must think more about rules for using memory and references as they program

Rust and typing

Primitive types

- `bool`
- `char` (4-byte unicode)
- `i8/i16/i32/i64/isize`
- `u8/u16/u32/u64/usize`
- `f32/f64`

Separate bool type

- C overloads an integer to get booleans
- Leads to varying interpretations in API calls
  - True, False, or Fail? 1, 0, -1?
  - Misinterpretations lead to security issues
  - Example: PHP strcmp returns 0 for both equality *and* failure!

Numeric types specified with width

- Prevents bugs due to unexpected promotion/coercion/rounding

Immutability by default

By default, Rust variables are immutable

- Usage checked by the compiler

mut is used to declare a resource as mutable.

```
fn main() {
    let a: i32 = 0;
    a = a + 1;
    println!("{}" , a);
}
```

```
rustc 1.14.0 (e8a012324 2016-12-16)
error[E0384]: re-assignment of immutable variable `a`
 --> <anon>:3:5
  |
2 |     let a: i32 = 0;
  |         - first assignment to `a`
3 |     a = a + 1;
  |     ^^^^^^^^^ re-assignment of immutable variable

error: aborting due to previous error
```

```
fn main() {
    let mut a: i32 = 0;
    a = a + 1;
    println!("{}" , a);
}
```

```
rustc 1.14.0 (e8a012324 2016-12-16)
1
Program ended.
```

Example: C is good

Lightweight, low-level control of memory

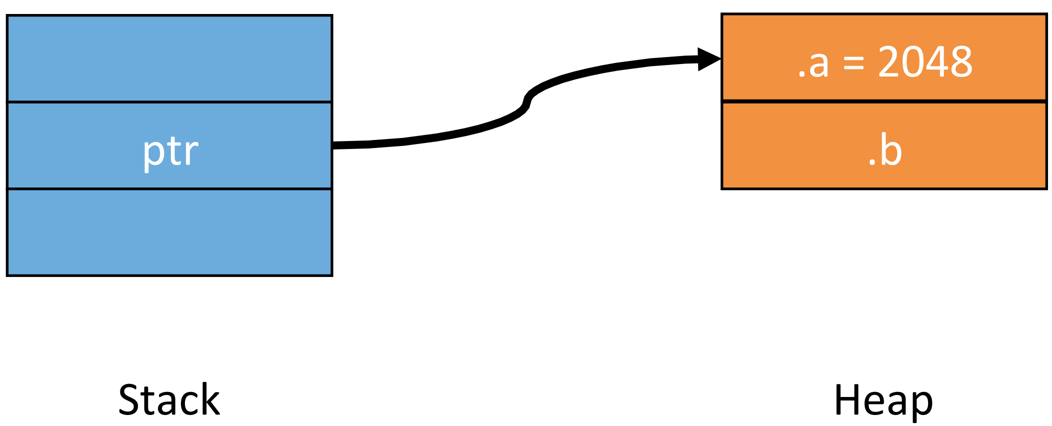
```c
typedef struct Dummy { int a; int b; } Dummy;

void foo(void) {
    Dummy *ptr = (Dummy *) malloc(sizeof(struct Dummy));
    ptr->a = 2048;
    free(ptr);
}
```

Precise memory layout

Lightweight reference

Destruction



Example: C is not so good

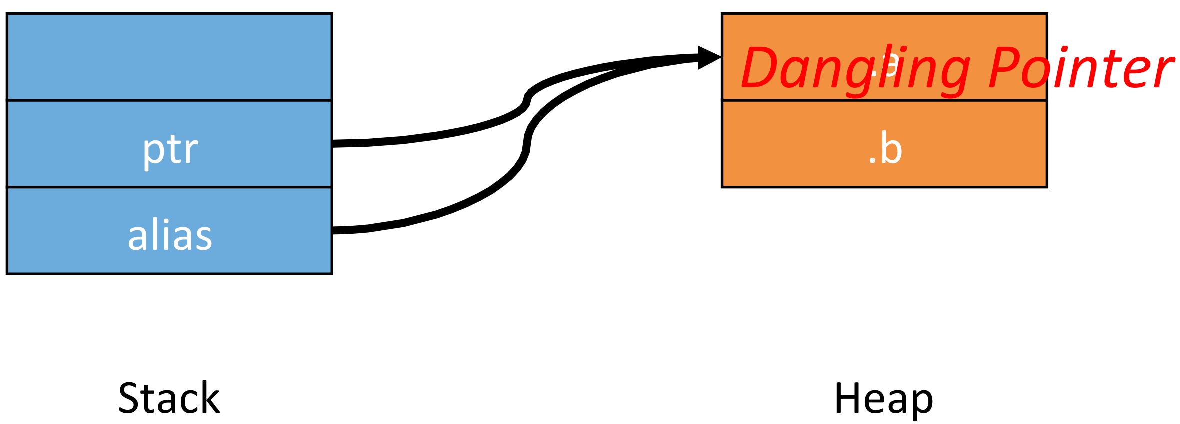
```c
typedef struct Dummy { int a; int b; } Dummy;

void foo(void) {
    Dummy *ptr = (Dummy *) malloc(sizeof(struct Dummy));
    Dummy *alias = ptr;
    free(ptr);
    int a = alias.a;
    free(alias);
}
```

Use after free

Double free

Aliasing ✚ *Mutation*



Other problems with aliasing + mutation

- Make programs more confusing
- May disallow some compiler's optimizations

```
int a, b, *p, *q;
   ...
a = *p;  /* read from the variable referred to by p*/

*q = 3; /* assign to the variable referred to by q */

b = *p; /* read from the variable referred to by p */
```

- Cause for a long time of inefficiency of C versus FORTRAN compilers

Solved by managed languages

Java, Python, Ruby, C#, Scala, Go...

- Restrict direct access to memory
- Run-time management of memory via periodic garbage collection
- No explicit malloc and free, no memory corruption issues
- But
  - Overhead of tracking object references
  - Program behavior unpredictable due to GC (bad for real-time systems)
  - Limited concurrency (global interpreter lock typical)
  - Larger code size
  - VM must often be included
  - Needs more memory and CPU power (i.e. not bare-metal)

Requirements for system programs

Must be fast and have minimal runtime overhead

Should support direct memory access, but be memory -safe

Rust’s Solution: Zero-cost Abstraction

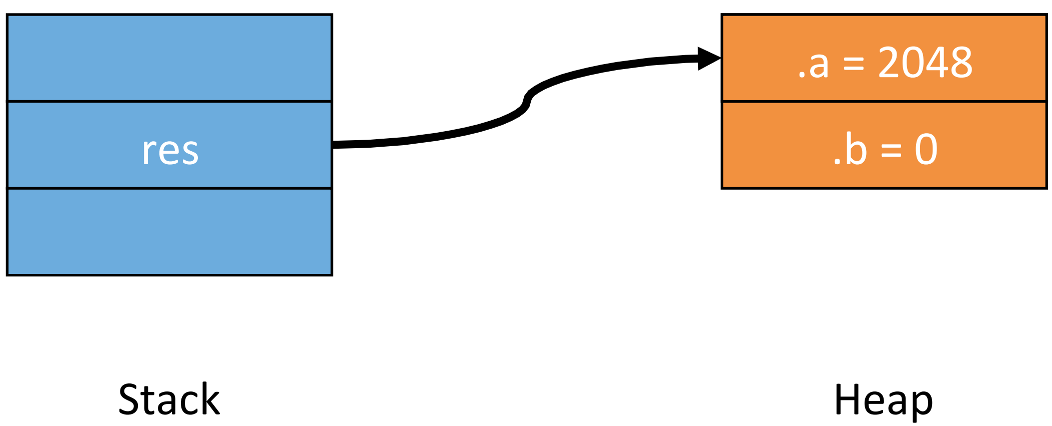
```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res: Box<Dummy> = Box::new(Dummy {
                                  a: 0,
                                  b: 0
                              });
    res.a = 2048;
}
```

Memory allocation

Variable binding

Resource owned by res *is freed automatically*



Side Slide: Type Inference

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res: Box<Dummy> = Box::new(Dummy {
                                  a: 0,
                                  b: 0
                              });
    res.a = 2048;
}
```

Rust's Solution: Ownership & Borrowing

~~*Aliasing*~~ + ~~*Mutation*~~

Compiler enforces:

- Every resource has a unique *owner*.
- Others can *borrow* the resource from its owner.
- Owner *cannot* free or mutate its resource while it is borrowed.

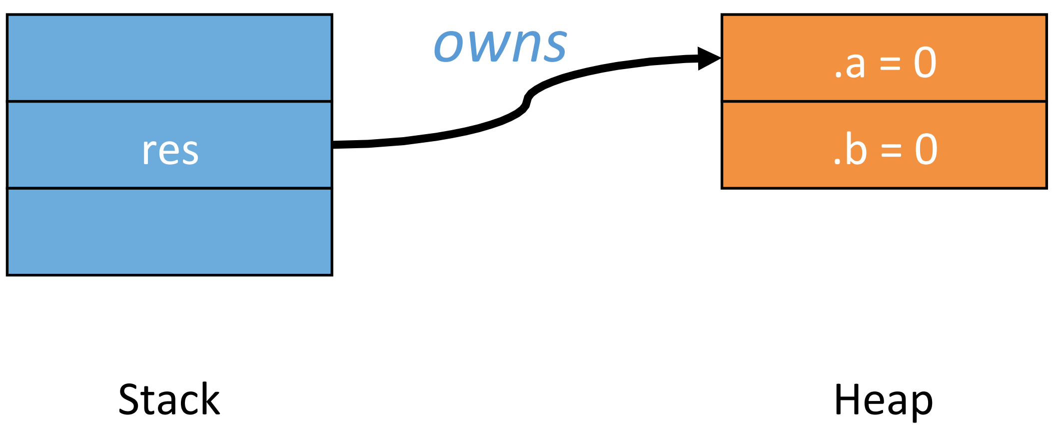
No need for runtime   Memory safety   Data-race freedom

Ownership

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy {
                    a: 0,
                    b: 0
                });
}
```

res is out of scope and its resource is freed automatically



Ownership: Lifetime

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res: Box<Dummy>;
    {
        res = Box::new(Dummy {a: 0, b: 0});
    }
    res.a = 2048;
}
```

Lifetime that res owns the resource.

Compiling Error: res no longer owns the resource

- Lifetime is determined and checked statically.
- Lifetimes are mostly inferred, but can be made explicit using generics

Ownership: Unique Owner

~~Aliasing~~ ✚ *Mutation*

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy {
                        a: 0,
                        b: 0
                    });
    take(res);
    println!("res.a = {}", res.a);
}

fn take(arg: Box<Dummy>) {
}
```

Compiling Error!

Ownership is moved from res to arg

arg is out of scope and the resource is freed automatically

Immutable/Shared Borrowing (&)

Aliasing ✚ ~~*Mutation*~~

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy{
                        a: 0,
                        b: 0
                    });
    take(&res);
    res.a = 2048;
}
```

Resource is returned from arg to res

Resource is immutably borrowed by arg from res

```
fn take(arg: &Box<Dummy>) {
    arg.a = 2048;
}
```

Compiling Error: Cannot mutate via an immutable reference

Resource is still owned by res. No free here.

Immutable/Shared Borrowing (&)

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy{a: 0, b: 0});
    {
        let alias1 = &res;
        let alias2 = &res;
        let alias3 = alias2;
        res.a = 2048;
    }
    res.a = 2048;
}
```

- Read-only sharing

Mutable Borrowing (&mut)

~~*Aliasing*~~ ✚ *Mutation*

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy{a: 0, b: 0});

    take(&mut res);
    res.a = 4096;

    let borrower = &mut res;
    let alias    = &mut res;
}

fn take(arg: &mut Box<Dummy>) {
    arg.a = 2048;
}
```

Mutably borrowed by arg from res

Multiple mutable borrowings are disallowed

Returned from arg to res

Concurrency & Data-race Freedom

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy {a: 0, b: 0});

    std::thread::spawn(move || {
        let borrower = &mut res;
        borrower.a += 1;
    });

    res.a += 1;
}
```

Spawn a new thread

res is mutably borrowed

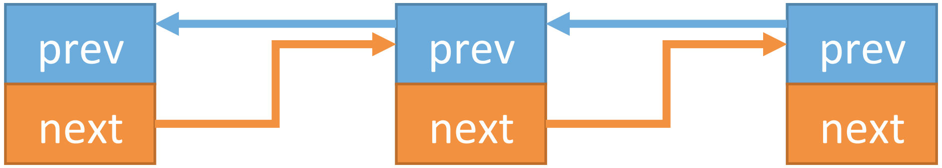
Error: res is being mutably borrowed

Unsafe

Life is hard.

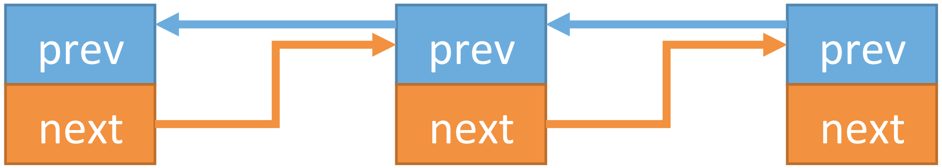
Mutably Sharing

- Mutably sharing is *inevitable* in the real world.
- Example: mutable doubly linked list




```
struct Node {
    prev: option<Box<Node>>,
    next: option<Box<Node>>
}
```

Rust’s Solution: Raw Pointers




```
struct Node {
    prev: option<Box<Node>>,
    next: *mut Node
}
```

Raw pointer

- Compiler does *NOT* check the memory safety of most operations *wrt.* raw pointers.
- Most operations *wrt.* raw pointers should be encapsulated in a *unsafe* {} syntactic structure.

Rust’s Solution: Raw Pointers

```
let a = 3;

unsafe {
    let b = &a as *const u32 as *mut u32;
    *b = 4;
}

println!(“a = {}”, a);
```

I know what I’m doing

Print “a = 4”

Foreign Function Interface (FFI)

- All foreign functions are unsafe.

```
extern {
    fn write(fd: i32, data: *const u8, len: u32) -> i32;
}

fn main() {
    let msg = b”Hello, world!\n”;
    unsafe {
        write(1, &msg[0], msg.len());
    }
}
```

Other Goodies

Enums, Pattern Match, Generic, Traits, Tests, …

Enums

- First-class
  - Instead of integers (C/C++)
- Structural
  - Parameters
  - Replacement of **union** in C/C++

Enums

```
enum RetInt {
    Fail(u32),
    Succ(u32)
}

fn foo_may_fail(arg: u32) -> RetInt {
    let fail = false;
    let errno: u32;
    let result: u32;
    ...
    if fail {
        RetInt::Fail(errno)
    } else {
        RetInt::Succ(result)
    }
}
```

Enums: No Null Pointers

```
enum std::option::Option<T> {
    None,
    Some(T)
}

struct SLStack {
    top: Option<Box<Slot>>
}

struct Slot {
    data: Box<u32>,
    prev: Option<Box<Slot>>
}
```

Pattern Match

```
let x = 5;

match x {
    1             => println!("one"),
    2             => println!("two"),
    3|4           => println!("three or four"),
    5 ... 10      => println!("five to ten"),
    e @ 11 ... 20 => println!("{}", e);
    _             => println!("others"),
}
```

Compiler enforces the matching is complete

Pattern Match

```
enum std::option::Option<T> {
    None,
    Some(T)
}

struct SLStack {
    top: Option<Box<Slot>>
}

fn is_empty(stk: &SLStack) -> bool {
    match stk.top {
        None     => true,
        Some(..) => false,
    }
}
```

Generic

```
struct SLStack {
    top: Option<Box<Slot>>
}

struct Slot {
    data: Box<u32>,
    prev: Option<Box<Slot>>
}

fn is_empty(stk: &SLStack) -> bool {
    match stk.top {
        None     => true,
        Some(..) => false,
    }
}
```

Generic

```rust
struct SLStack<T> {
    top: Option<Box<Slot<T>>>
}

struct Slot<T> {
    data: Box<T>,
    prev: Option<Box<Slot<T>>>
}

fn is_empty<T>(stk: &SLStack<T>) -> bool {
    match stk.top {
        None     => true,
        Some(..) => false,
    }
}
```

Traits

- More generic
- Typeclass in Haskell

Traits

Type implemented this trait

Object of the type implementing this trait

```
trait Stack<T> {
   fn new() -> Self;
   fn is_empty(&self) -> bool;
   fn push(&mut self, data: Box<T>);
   fn pop(&mut self) -> Option<Box<T>>;
}

impl<T> Stack<T> for SLStack<T> {
    fn new() -> SLStack<T> {
        SLStack{ top: None }
    }

    fn is_empty(&self) -> bool {
        match self.top {
            None     => true,
            Some(..) => false,
        }
    }
}
```

Using Traits for Bounded Polymorphism

```rust
trait Stack<T> {
   fn new() -> Self;
   fn is_empty(&self) -> bool;
   fn push(&mut self, data: Box<T>);
   fn pop(&mut self) -> Option<Box<T>>;
}

fn generic_push<T, S: Stack<T>>(stk: &mut S,
                                data: Box<T>) {
    stk.push(data);
}

fn main() {
    let mut stk = SLStack::<u32>::new();
    let data = Box::new(2048);
    generic_push(&mut stk, data);
}
```

Multiple traits as bounds

```
trait Clone {
    fn clone(&self) -> Self;
}

impl<T> Clone for SLStack<T> {
    ...
}

fn immut_push<T, S: Stack<T>+Clone>(stk: &S, data: Box<T>) -> S
{
    let mut dup = stk.clone();
    dup.push(data);
    dup
}

fn main() {
    let stk = SLStack::<u32>::new();
    let data = Box::new(2048);
    let stk = immut_push(&stk, data);
}
```

Learning & Development Resources

Official Resources

- Rust website: http://rust-lang.org/
- Playground: https://play.rust-lang.org/
- Guide: https://doc.rust-lang.org/stable/book/
- Documents: https://doc.rust-lang.org/stable/
- User forum: https://users.rust-lang.org/
- Dev forum: https://internals.rust-lang.org/
- Source code: https://github.com/rust-lang/rust
- IRC: server: *irc.mozilla.org*, channel: *rust*
- Cargo: https://crates.io/

3rd Party Resources

- Rust by example: http://rustbyexample.com/
- Reddit: https://reddit.com/r/rust
- Stack Overflow: https://stackoverflow.com/questions/tagged/rust

Academic Research

- https://doc.rust-lang.org/stable/book/academic-research.html

Projects

- rustc: Rust compiler
  - https://github.com/rust-lang/rust
- Cargo: Rust's package manager
  - https://github.com/rust-lang/cargo
- Servo: Experimental web browser layout engine
  - https://github.com/servo/servo
- Piston: A user friendly game engine
  - https://github.com/PistonDevelopers/piston
- Iron: An extensible, concurrent web framework
  - https://github.com/iron/iron
- On Github
  - https://github.com/trending?l=rust

Development Environment

- Microsoft Visual Studio
  - Rust plugin: https://visualstudiogallery.msdn.microsoft.com/c6075d2f-8864-47c0-8333-92f183d3e640
- Emacs
  - rust-mode: https://github.com/rust-lang/rust-mode
  - racer: https://github.com/phildawes/racer
  - flycheck-rust: https://github.com/flycheck/flycheck-rust
- Vim
  - rust.vim: https://github.com/rust-lang/rust.vim
  - racer: https://github.com/rust-lang/rust.vim