CMSC 330: Organization of Programming Languages

Type-Safe, Low-level Programming with **Rust**

Type Safety in Programming Languages

- In a type-safe language, the type system enforces well defined behavior. Formally, a language is type-safe *iff*

$$G \vdash \mathbf{e} : \mathbf{t} \text{ and } G \vdash A \text{ implies}$$

$$A;\ \mathbf{e} \Rightarrow \mathbf{v} \text{ and } \vdash \mathbf{v} : \mathbf{t} \text{ or that } \mathbf{e} \text{ runs forever}$$

- $A;\ \mathbf{e} \Rightarrow \mathbf{v}$ says $\mathbf{e}$ *evaluates* $\mathbf{v}$ under environment A
- $G \vdash \mathbf{e} : \mathbf{t}$ says $\mathbf{e}$ *has type* $\mathbf{t}$ under type environment G
- $G \vdash A$ says A *is compatible with* G
  - For all $\mathbf{x}$, $A(\mathbf{x}) = \mathbf{v}$ implies $G(\mathbf{x}) = \mathbf{t}$ and $\vdash \mathbf{v} : \mathbf{t}$

C/C++: *Not* Type-Safe – Spatially Unsafe

$G \vdash e : t$ and $G \vdash A$ implies

$A; e \Rightarrow v$ and $\vdash v : t$ or that e runs forever

Type safety is violated by buffer overflows

```
int main() {
  int x = 1, *p = &x;
  int y = 0, *q = &y;
  *(q+1) = 5; // overwrites p
  return *p; // crash
}
```

C/C++: *Not* Type-Safe – Temporally Unsafe

and dangling pointers (uses of pointers to freed memory)

```
{ int *x = ...malloc();
  free(x);
  *x = 5; /* oops! */
}
```

… which can happen via the stack, too:

```
int *foo(void) { int z = 5; return &z; }
void bar(void) {
  int *x = foo();
  *x = 5; /* oops! */
}
```

Automatic Memory Management

- Data may be allocated explicitly or implicitly. Data reclamation occurs automatically: No manual **`free`**

- A garbage collector traces pointers in use by the program, starting from the stack and global variables
  - Retains those objects it can reach (since could be used later)
  - Reclaims those it cannot
- Related technique: Reference counting

- Both impose space and run-time costs

Memory Management in (Type-Safe) OCaml

- Local variables live on the stack
- Tuples, closures, and constructed types live on the heap

```
let x = (3, 4)   (* heap-allocated *)
let f x y = x + y in f 3
                    (* result heap-allocated *)
type 'a t = None | Some of 'a
None        (* not on the heap–just a primitive *)
Some 37     (* heap-allocated *)
```

- Heap data reclaimed via garbage collection

In sum: What choice do programmers have?

C/C++

- **Type-unsafe**
- **Low level** control
- **Performance** over safety and ease of use
- **Manual** memory management, e.g., with **malloc/free**

Java, OCaml, Go, Ruby…

- **Type safe**
- **High level**, less control
- **Ease-of-use** and **safety** over performance
- **Automatic** memory management via **garbage collection**
  - No explicit malloc/free

Something in between … ?

Rust: Type-safe (and Thread-safe), and Fast

- A Mozilla-sponsored, public project since 2010
  - Started in 2006 by Graydon Hoare while at Mozilla
- Most loved programming language in Stack Overflow annual surveys every year from 2016 through 2020
- Key properties: Type safety, and no data races, despite use of concurrency and manual memory management

Rust in the Real World

- Firefox Quantum and Servo components
  - https://servo.org
- REmacs port of Emacs to Rust
  - https://github.com/Wilfred/remacs
- Amethyst game engine
  - https://www.amethyst.rs/
- Magic Pocket filesystem from Dropbox
  - https://www.wired.com/2016/03/epic-story-dropboxs-exodus-amazon-cloud-empire/
- OpenDNS malware detection components
- https://www.rust-lang.org/en-US/friends.html

Features of Rust

- Lifetimes and Ownership
  - Key feature for ensuring safety
- Traits as core of object(-like) system
- Variable default is immutability
- Data types and pattern matching
- Type inference
  - No need to write types for local variables
- Generics (aka parametric polymorphism)
- First-class functions
- Efficient C bindings

Takes ideas from functional and OO languages, and recent research

Installing Rust

- Instructions, and stable installers, here:

  https://www.rust-lang.org/en-US/install.html

- On a Mac or Linux (VM), open a terminal and run

  curl https://sh.rustup.rs -sSf | sh

- On Windows, download+run rustup-init.exe

  https://static.rust-lang.org/rustup/dist/i686-pc-windows-gnu/rustup-init.exe

Rust Compiler, Build System

- Rust programs can be compiled using rustc
  - Source files end in suffix .rs
  - Compilation, by default, produces an executable
    - No –c option

- Preferred: Use the cargo package manager
  - Will invoke rustc as needed to build files
  - Will download and build dependencies
  - Based on a .toml file and .lock file
    - You won't have to mess with these for this class
  - Like ocamlbuild or dune

Using cargo

- Make a project, build it, run it

```
% cargo new hello_cargo --bin
% cd hello_cargo
% ls
Cargo.toml   src/
% ls src
main.rs
% cargo build
 Compiling hello_cargo v0.1.0 (file:///…)
 Finished dev [unoptimized + debuginfo] …
% ./target/debug/hello_cargo
Hello, world!
```

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

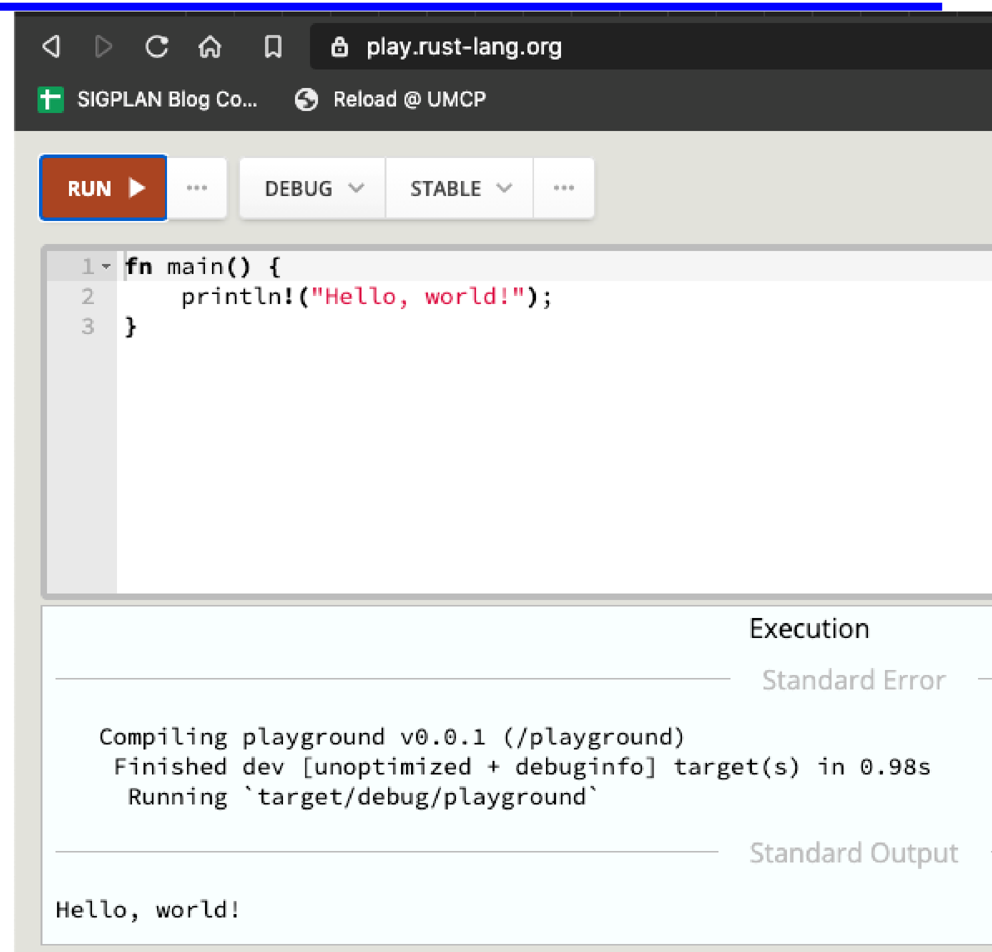
Use `cargo` to run tests, too; will discuss later

Uses **`rustc`**, the Rust compiler

More at https://doc.rust-lang.org/stable/cargo/getting-started/first-steps.html

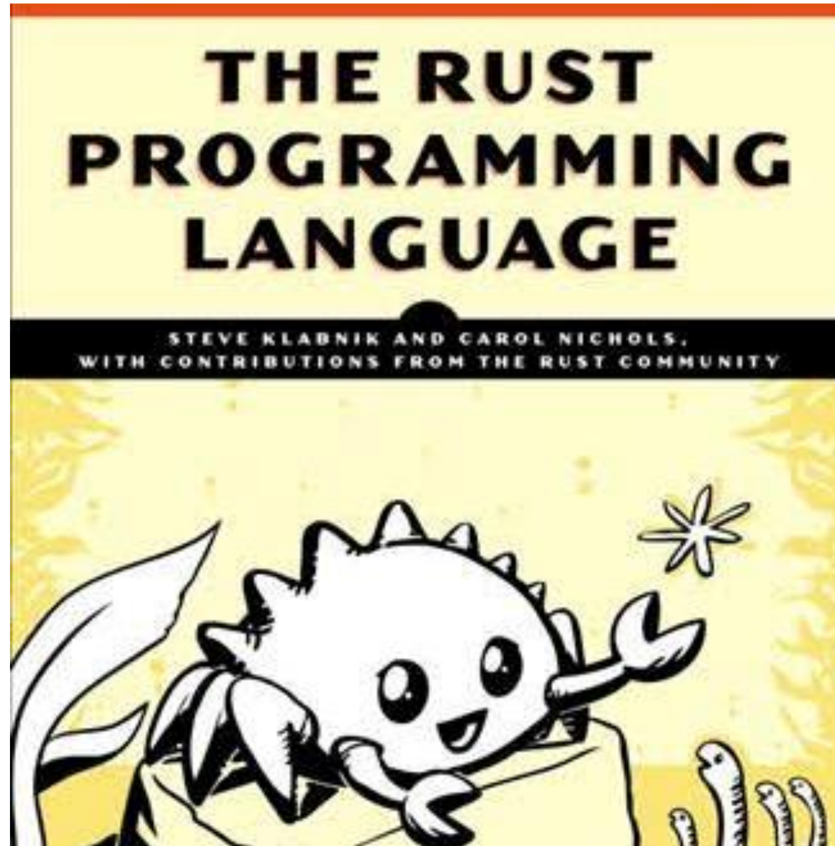
Rust, Interactively

- Rust has no top-level *a la* OCaml or Ruby
- There is an in-browser execution environment
  - https://play.rust-lang.org/



Rust Documentation

- Rust documentation is a good reference, and way to learn
  - https://doc.rust-lang.org/stable/
- This contains links to
  - the Rust Book (on which most of our slides are based)
  - the reference manual, and
  - short manuals on the compiler, cargo, and more



Rust Basics

Functions

```
//  comment
fn main() {
    println!("Hello, world!");
}
```

```
Hello, world!
```

Let Statements

```
{
  let x = 37;
  let y = x + 5;
  y
}//42
```

```
{
  let x = 37;
  x = x + 5;//err
  x
}
```

```
{ //err:
  let x:u32 = -1;
  let y = x + 5;
  y
}
```

```
{
  let x = 37;
  let x = x + 5;
  x
}//42
```

```
{
  let mut x = 37;
  x = x + 5;
  x
}//42
```

```
{
  let x:i16 = -1;
  let y:i16 = x+5;
  y
}//4
```

Redefining a variable *shadows* it (like OCaml); aim to avoid

Variables immutable by default; use **`mut`** to allow updates

Types inferred by default; optional annotations must be consistent (may override defaults)

Conditionals

```
fn main() {
  let n = 5;
  if n < 0 {
    print!("{} is negative", n);
  } else if n > 0 {
    print!("{} is positive", n);
  } else {
    print!("{} is zero", n);
  }
}
```

5 is positive

Conditionals are *Expressions* (like OCaml)

```
fn main() {
  let n = 5;
  let x = if n < 0 {
    10
  } else {
    "a"
  };
  print!("{:?}|",x);
}
```

Type error

Factorial in Rust (recursively)

```
fn fact(n:i32) -> i32
{
  if n == 0 { 1 }
  else {
    let x = fact(n-1);
    n * x
  }
}

fn main() {
  let res = fact(6);
  println!("fact(6) = {}",res);
}
```

```
fact(6) = 720
```

Quiz: What does this evaluate to?

```
{ let x = 6;
  let y = "hi";
  if x == 5 { y } else { 5 };
  7
}
```

A. 6
B. 7
C. 5
D. Error

Quiz: What does this evaluate to?

```
{ let x = 6;
  let y = "hi";
  if x == 5 { y } else { 5 };
  7
}
```

A. 6
B. 7
C. 5
D. Error – if and else have incompatible types

Quiz: What does this evaluate to?

```
{ let x = 6;
  let y = 4;
  y = x;
  x == y
}
```

A. 6
B. true
C. false
D. error

Quiz: What does this evaluate to?

```
{ let x = 6;
  let y = 4;
  y = x;
  x == y
}
```

A. 6
B. true
C. false
D. error – y is immutable

Using Mutation

- Mutation is useful when performing iteration
  - As in C and Java

```
fn fact(n: u32) -> u32 {
   let mut x = n;
   let mut a = 1;
   loop {
     if x <= 1 { break; }
     a = a * x;
     x = x - 1;
   }
   a
}
```

infinite loop
(break out)

Other Looping Constructs

- While loops
  - **`while`** ***e block***
- For loops
  - **`for`** ***pat*** **`in`** ***e block***
    - More later – e.g., for iterating through collections

```
for x in 0..10 {
  println!("{}", x); // x: i32
}
```

Other Looping Constructs

- These (and **`loop`**) are *expressions*
  - They return the final computed value
    - unit, if none
  - **`break`** may take an expression, which is the loop's final value

```
let mut x = 5;
let y = loop {
  x += x - 3;
  println!("{}", x);// 7 11 19 35
  x % 5 == 0 { break x; }
};
print!("{}",y); //35
```

Quiz: What does this evaluate to?

```
let mut x = 1;
for i in 1..6 {
  let x = x + 1;
}
x
```

A. 1
B. 6
C. 0
D. error

Quiz: What does this evaluate to?

```
let mut x = 1;
for i in 1..6 {
  let x = x + 1;
}
x
```

A. **1**
B. 6
C. 0
D. error

Data: Scalar Types

- Integers
  - **`i8`**, **`i16`**, **`i32`**, **`i64`**, **`isize`**
  - **`u8`**, **`u16`**, **`u32`**, **`u64`**, **`usize`**
- Characters (unicode)
  - **`char`**
- Booleans
  - **`bool`** = { **`true`**, **`false`** }
- Floating point numbers
  - **`f32`**, **`f64`**
- Note: arithmetic operators (+, -, etc.) *overloaded*

Machine word size

Defaults (from inference)

Compound Data: Tuples

- Tuples
  - n-tuple type **(*t1*,…,*tn*)**
    - **unit ()** is just the 0-tuple
  - n-tuple expression **(*e1*,…,*en*)**
  - Accessed by pattern matching or like a record field

```
let tuple = ("hello", 5, 'c');
assert_eq!(tuple.0, "hello");
let(x,y,z) = tuple;
```

Compound Data: Tuples

Distance between two points **s** and **e**

```
fn dist(s:(f64,f64),e:(f64,f64)) -> f64 {
  let (sx,sy) = s;
  let ex = e.0;
  let ey = e.1;
  let dx = ex - sx;
  let dy = ey - sy;
  (dx*dx + dy*dy).sqrt()
}
```

Compound Data: Tuples

Can include patterns in parameters directly, too

```
fn dist2((sx,sy):(f64,f64),(ex,ey):(f64,f64)) -> f64 {
    let dx = ex - sx;
    let dy = ey - sy;
    (dx*dx + dy*dy).sqrt()
}
```

We'll see Rust **`struct`**s later. They generalize tuples.

Arrays: Standard Operations

- Creating an array (can be mutable or not)
  - But must be of fixed length
- Indexing an array
- Assigning at an array index

```
let nums = [1,2,3]; // type is [i32;3]
let strs = ["Monday","Tuesday","Wednesday"]; //[&str;3]
let x = nums[0]; // 1
let s = strs[1]; // "Tuesday"
let mut xs = [1,2,3];
xs[0] = 1; // OK, since xs mutable
let i = 4;
let y = nums[i]; //fails (panics) at run-time
```

Arrays: Iteration

- Rust provides a way to iterate over a collection
  - Including arrays

```
let a = [10,20,30,40,50];
for element in a.iter() {
  println!("the value is: {}", element);
}
```

  - **`a.iter()`** produces an iterator, like a Java iterator
    - This is a method call, *a la* Java. More about these later
  - The special **`for`** syntax issues the **`.next()`** call until no elements are left
    - No possibility of running out of bounds

Quiz: Will this function type check?

```
fn f(n:[u32]) -> u32 {
  n[0]
}
```

A. Yes

B. No

Quiz: Will this function type check?

```
fn f(n:[u32;len]) -> u32 {
  n[0]
}
```

A. Yes

B. No – because array length not known. Need to fill in `len`

Testing

- In any language, there is the need to test code
- In most languages, testing requires extra libraries:
  - Minitest in Ruby
  - Ounit in Ocaml
  - Junit in Java
- Testing in Rust is a first-class citizen!
  - The testing framework is built into cargo

Unit Testing In Rust

- Unit testing is for local or private functions
  - Put such tests in the same file as your code

- Use `assert!` to test that something is true
- Use `assert_eq!` to test that two things that implement the `PartialEq` trait are equal
  - E.g., integers, booleans, etc.
  - We'll explain traits later on

Unit Testing In Rust

```
fn bad_add(a: i32, b: i32) -> i32 {
    a - b
}

#[cfg(test)]
mod tests {
  #[test]
  fn test_bad_add() {
    assert_eq!(bad_add(1,2),3);
  }
}
```

This is a *module*, **`tests`**

Indicates that this module contains tests

Indicates that this function is a test

Integration Testing In Rust

- Integration testing is for APIs and whole programs

- Create a **`tests`** directory
- Create different files for testing major functionality
- Files don't need **`#[cfg(test)]`** or a special module
  - But they do still need **`#[test]`** around each function
- Tests refer to code as if it were an external library
  - Declare it as an external library using **`extern crate`**
  - Include the functionality you want to test with **`use`**

Integration Testing In Rust

src/lib.rs

```
pub fn add(a: i32, b: i32) -> i32 {
  a + b
}
```

tests/test_add.rs

```
extern crate my-project-name;
use my-project-name::add;
#[test]
pub fn test_add() {
        assert_eq!(add(1,2), 3));
}
#[test]
pub fn test_negative_add() {
        assert_eq!(add(1,-2), -1));
}
```

Running Tests

- **`cargo test`** runs all of your tests
- **`cargo test`** ***`s`*** runs all tests that contain ***`s`*** in the name
- By default, console output is hidden
  - Use **`cargo test -- --nocapture`** to un-hide it

Fun Fact

- The original Rust compiler was written in OCaml
  - Betrays the sentiments of the language's designers!
- Now the Rust compiler is written in … Rust
  - How is this possible? Through a process called bootstrapping:
    - The first Rust compiler written in Rust is compiled by the Rust compiler written in OCaml
    - Now we can use the binary from the Rust compiler to compile itself
    - We discard the OCaml compiler and just keep updating the binary through self-compilation
    - So don't lose that binary! ☺