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Intro to Rust

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What is Rust

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- systems programming language
- compiled
- strongly, statically typed
- low-level access, high-level abstractions
- "curly-braced" (C-like)
- large community
- multi-paradigm
- inspired by: C++, Erlang, Haskell, OCaml, Swift, ...

History (up to 1.0)

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from 2006	personal project of Graydon Hoare compiler in OCaml
since 2009	development supported by Mozilla, as part of Mozilla Research
since 2011	self-hosting
since 2014	language changes through RFC process
May 2015	release of Rust 1.0

History (after 1.0)

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2019	async-await syntax and futures
2020	Mozilla layoffs affecting Rust
since 2021	Rust Foundation
2018, 2021, 2024	new Rust “editions”

Philosophy

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- memory-safe
  - no use-after-free
  - no out-of-bounds accesses
- make data races impossible
- no runtime or mandatory garbage collector
- make costs explicit
- enforce handling error conditions
- immutable by default
- zero-cost abstractions

Fields of Application

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- CLI tools
- Web Services
- WebAssembly
- Embedded Systems
- ...

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Enums

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```rust
// C-like
enum Dir {
    North,
    East,
    South,
    West
}
let d: Dir = Dir::East;
```

```rust
// with associated data
enum Shape {
    Rect { x: f32, y: f32 },
    Circle { r: f32 }
}
let c: Shape = Shape::Circle {
    r: 23.0
};
```

- sum type
- similar to a tagged union

Example: Option


```
1 enum Option<T> {
2     None,
3     Some(T)
4 }
```

- equivalent to Haskell's Maybe monad (`return = Some`, `bind = and_then`)
- used instead of NULL-pointers, nil-objects, etc.

Example: Option

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```rust
let entity = "#x21";
let val = entity
    .strip_prefix("#x")
    .and_then(|val| u32::from_str_radix(val, 16).ok());
assert_eq!(val.and_then(char::from_u32), Some('!'));
```

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match

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```rust
let x = 2u32;

match x {
    1 => "One",
    2 | 3 => "Twree",
    5..9 => "Large small number",
    _ => "Fallthrough"
}
```

match

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```rust
let d = Dir::East;

match d {
    Dir::North => println!("Northwards!")
    Dir::East => println!("Go East!")
    Dir::South => println!("Southwards!")
    Dir::West => println!("Go West!")
}
```

match

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```rust
match x.checked_add(y) {
    Some(res) => println!("{res}"),
    None => println!("Overflow"),
}
```

match

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```rust
let c = Shape::Circle { r: 1.0 };

match c {
    Shape::Rect { x, y } => println!("{x} x {y}"),
    Shape::Circle { r } => println!("{r}"),
}
```

let

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```rust
let Person { age, name } = marv;
let (x, y) = point;
let Person { age: edad, name: nombre } = marv;
```

if let

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```
1 if let Ok(dir) = std::env::var("HOME") {
2     println!("Home directory is {}", dir);
3 }
```

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Iterators

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- implemented with an associated function
  `fn next(&mut self) -> Option<Item>`
- `for`-loops are syntactic sugar for repeatedly calling `next()` until it returns `None`
- lots of "adapters" for functional-style programming

Example: Iterator Adaptors

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```rust
fn main() {
    let mult = (1u32..)
        .filter(|x| (1..11).all(|y| x.is_multiple_of(y)))
        .next()
        .unwrap();
    println!("{}", mult);
}
```

- finds the smallest number evenly divisible by every number from 1 through 10

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Why?

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- systems programming can be scary
- a lot of bugs concern memory safety and data races
- (most) systems language do not protect against them
- Rust's ownership model rules out these classes of bugs

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C++: Realloc

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```cpp
#include <iostream>
#include <vector>
#include <string>

int main() {
    auto v = std::vector<std::string> { "Foo" };

    std::cout << "Capacity: " << v.capacity() << '\n';
    auto const &x = v[0];
    v.emplace_back("Bar");
    std::cout << x << '\n';
}
```

C++: Realloc

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```
$ clang++ -Wall -O1 vector.cc -o vector-cc
$ ./vector-cc
Capacity: 1
Segmentation fault (core dumped)
```

C++: Iterator Invalidation

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```cpp
#include <iostream>
#include <string>
#include <vector>

int main() {
    std::vector<std::string> v = { "F", "o", "o" };

    for (auto const &it : v) {
        v.push_back(it + it);
    }
    for (auto const &it : v) {
        std::cout << it << '\n';
    }
}
```

C++: Iterator Invalidation


```
$ clang++ -Wall iter.cc -o iter-cc
$ ./iter-cc
F
o
o
FF


$
```

C++: Use After Free


```cpp
#include <iostream>
#include <memory>

int& f() {
    auto i = std::make_unique<int>(42);
    auto &i_ref = *i;
    return i_ref;
}

int main() {
    int &i = f();
    std::cout << i << '\n';
}
```

C++: Use After Free

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```
$ clang++ -Wall after-free.cc -o after-free
$ ./after-free
-662549570
$
```

C++: Type punning

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```
3  struct Foo {
4      int field;
5  };
6
7  void f(Foo &foo, float const *x) {
8      auto a = *x + 42.0;
9      foo.field = 0x7fffffff;
10     auto b = *x + 42.0;
11     std::cout << a << ' ' << b << '\n';
12 }
13
14 int main() {
15     Foo foo { 12 };
16     f(foo, reinterpret_cast<float*>(&foo.field));
17 }
```

C++: Type punning

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```
$ clang++ -Wall field.cc -o field-cc
$ ./field-cc
42 nan
$ clang++ -Wall -O1 field.cc -o field-cc
$ ./field-cc
42 42
```

Observation

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Problems arise when combining:

Mutability

```
v.emplace_back(...)
v.push_back(...)
foo.field = 0x7fffffff;
```

+

Aliasing

```
auto const &x = v[0]
auto const &it : v
foo, &foo.field
```

Rust prevents this by ensuring an object is never mutable and aliased.

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Ownership: Bindings

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```
1  struct Crop;
2
3  fn main() {
4      let c = Crop;
5
6      // moves c to _miller1
7      let _miller1 = c;
8
9      // error: use of moved value: `c`
10     let _miller2 = c;
11 }
```

Ownership: Functions

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```
1  struct Crop;
2  struct Flour;
3
4  fn grind(_c: Crop) -> Flour {
5      Flour
6      // _c is freed here
7  }
8
9  fn main() {
10     let c = Crop;
11
12     grind(c); // c moves into grind()
13     // error: use of moved value: `c`
14     grind(c);
15 }
```

Returning Ownership

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```rust
struct Book { page: u32 }

fn read(b: Book) -> Book {
    println!("I read page {}", b.page);
    b
}

fn main() {
    let b = Book { page: 1 };
    // b moves into `read()`
    let b1 = read(b);
    // error: use of moved value: `b`
    // let b2 = read(b);
    let _b2 = read(b1);
}
```

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Shared Borrow

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```
1  struct Book { page: u32 }
2
3  fn read(b: &Book) {
4      println!("I read page {}", b.page);
5  }
6
7  fn main() {
8      let b = Book { page: 1 };
9      let l = &b;
10
11     read(&b);
12     read(l);
13     read(&b);
14 }
```

Mutable Borrow

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```
7  fn turn_page(b: &mut Book) { b.page += 1; }
8
9  fn main() {
10     let mut b = Book { page: 1 };
11
12     read(&b);
13     turn_page(&mut b);
14     read(&b);
15
16     let l = &b;
17     // turn_page(&mut b); // error: cannot borrow `b` as
18                           // mutable because it is also
19                           // borrowed as immutable
20     read(l);
21 }
```

Exception: Copy Types

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```rust
struct Dress;
#[derive(Copy, Clone)]
struct Mp3;

fn main() {
    let shop_dress = Dress;
    let _your_dress = shop_dress;
    // error: use of moved value: `shop_dress`
    let _their_dress = shop_dress;

    let shop_mp3 = Mp3;
    let _your_mp3 = shop_mp3;
    // This is fine
    let _their_mp3 = shop_mp3;
}
```

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- Ownership: `T`
  - one owner
  - readable
  - mutable†
  - can be moved or borrowed

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- Ownership: `T`
  - one owner
  - readable
  - mutable†
  - can be moved or borrowed
- Shared borrow: `&T`
  - arbitrarily shareable (aliasing)
  - readable
  - immutable

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- Ownership: `T`
  - one owner
  - readable
  - mutable†
  - can be moved or borrowed
- Shared borrow: `&T`
  - arbitrarily shareable (aliasing)
  - readable
  - immutable
- Mutable borrow: `&mut T`
  - only one at a time
  - readable
  - mutable

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Example: Calculating π

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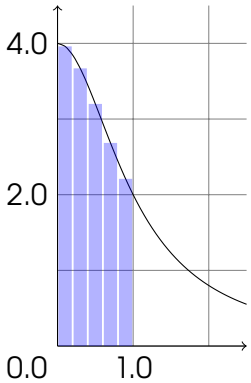
$$\pi = 4 \arctan(1)$$
$$= \int_0^1 \frac{4}{1+x^2} \, \mathrm{d}x$$

- calculate π by Riemann integration
- approximate the area with thin rectangles
- embarrassingly parallel



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Free-Threaded Python: Data Race

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```python
from threading import Thread

NUM_THREADS = 4
NUM_STEPS = 100_000_000
THREAD_STEPS = NUM_STEPS // NUM_THREADS
STEP = 1.0 / NUM_STEPS

pi = 0.0

def threadFunc(lower, upper):
    global pi
    for j in range(lower, upper):
        x = (j + 0.5) * STEP
        pi += 4.0 / (1.0 + x * x) * STEP
```

Free-Threaded Python: Data Race

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```
16 threads = []
17 for i in range(NUM_THREADS):
18     lower = THREAD_STEPS * i
19     upper = THREAD_STEPS * (i + 1)
20     t = Thread(target=threadFunc, args=(lower, upper))
21     threads.append(t)
22
23 for t in threads:
24     t.start()
25
26 for t in threads:
27     t.join()
28
29 print(f"Pi = {pi}")
```

Free-Threaded Python: Data Race

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```
$ python3.13t pi.py
Pi = 1.0351948517209917
$ python3.13t pi.py
Pi = 1.0590036387978847
```

- thread A reads `pi = 0.1423`
- thread B reads `pi = 0.1423`
- thread A writes `pi = 0.7609`
- thread B writes `pi = 0.5768`
- `pi = 0.5768`, thread A's calculation is lost
- this is a classical data race

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C++: Data Race

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```cpp
#include <cstdint>
#include <print>
#include <thread>
#include <vector>

int main() {
  constexpr uint64_t NUM_THREADS = 4;
  constexpr uint64_t NUM_STEPS = 100'000'000;
  constexpr uint64_t THREAD_STEPS = NUM_STEPS / NUM_THREADS;
  constexpr double STEP = 1.0 / NUM_STEPS;

```

C++: Data Race

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```
12    double pi = 0;
13
14    std::vector<std::thread> threads;
15
16    for (uint64_t i = 0; i < NUM_THREADS; ++i) {
17      uint64_t lower = THREAD_STEPS * i;
18      uint64_t upper = THREAD_STEPS * (i + 1);
19      threads.emplace_back([=, &pi]() {
20        for (uint64_t j = lower; j < upper; ++j) {
21          double x = (j + 0.5) * STEP;
22          pi += 4.0 / (1.0 + x * x) * STEP;
23        }
24      });
25    }
```

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```
26
27      for (auto &t : threads)
28        t.join();
29
30      std::println("Pi = {:.10}", pi);
31
32      return 0;
33  }
```

C++: Data Race

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```
$ clang++ -Wall -std=c++23 -lpthread pi.cc -o pi-cc
$ ./pi-cc
Pi = 1.156130797
$ ./pi-cc
Pi = 1.099799814
```

- thread A reads `pi = 0.1423`
- thread B reads `pi = 0.1423`
- thread A writes `pi = 0.7609`
- thread B writes `pi = 0.5768`
- `pi = 0.5768`, thread A's calculation is lost
- this is a classical data race

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A Naïve Port


```rust
use std::thread;

fn main() {
    const NUM_THREADS: u32 = 4;
    const NUM_STEPS: u32 = 100_000_000;
    const THREAD_STEPS: u32 = NUM_STEPS / NUM_THREADS;
    const STEP: f64 = 1.0 / NUM_STEPS as f64;

```

A Naïve Port

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```
9       let mut pi: f64 = 0.0;
10
11      let mut guards = Vec::new();
12      for i in 0..NUM_THREADS {
13          let lower: u32 = THREAD_STEPS * i;
14          let upper: u32 = THREAD_STEPS * (i + 1);
15          let pi_ref: &mut f64 = &mut pi;
16          guards.push(thread::spawn(move || {
17              for j in lower..upper {
18                  let x: f64 = (f64::from(j) + 0.5) * STEP;
19                  *pi_ref += 4.0 / (1.0 + x * x) * STEP;
20              }
21          }));
22      }
```

A Naïve Port


```
23
24      for g in guards {
25          g.join().unwrap();
26      }
27
28      println!("Pi = {:.10}", pi);
29  }
```

A Naïve Port

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```
error[E0597]: `pi` does not live long enough
  --> pi.rs:15:32
   |
9  |       let mut pi: f64 = 0.0;
   |           ------ binding `pi` declared here
...
15 |           let pi_ref: &mut f64 = &mut pi;
   |                                   ^^^^^^^ borrowed value does not live long enough
16 |           guards.push(thread::spawn(move || {
   |  _____________________-
17 | |             for j in lower..upper {
18 | |                 let x: f64 = (f64::from(j) + 0.5) * STEP;
19 | |                 *pi_ref += 4.0 / (1.0 + x * x) * STEP;
20 | |             }
21 | |         }));
   | |__________- argument requires that `pi` is borrowed for `'static`
...
29 |   }
   |   - `pi` dropped here while still borrowed
```

Spawned threads could live past `main()`.
Therefore, borrowed data needs to live indefinitely.

Adding Some Scope

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```
9       let mut pi: f64 = 0.0;
10
11      thread::scope(|scope| {
12          for i in 0..NUM_THREADS {
13              let lower: u32 = THREAD_STEPS * i;
14              let upper: u32 = THREAD_STEPS * (i + 1);
15              let pi_ref: &mut f64 = &mut pi;
16              scope.spawn(move || {
17                  for j in lower..upper {
18                      let x: f64 = (f64::from(j) + 0.5) * STEP;
19                      *pi_ref += 4.0 / (1.0 + x * x) * STEP;
20                  }
21              });
22          }
23      });
```

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```
error[E0499]: cannot borrow `pi` as mutable more than once at a time
  --> pi-scoped.rs:15:36
   |
11 |       thread::scope(|scope| {
   |                      ----- has type `&'1 Scope<'1, '_>`
...
15 |               let pi_ref: &mut f64 = &mut pi;
   |                                      ^^^^^^^ `pi` was mutably borrowed here
   |                                              in the previous iteration of the loop
16 | /             scope.spawn(move || {
17 | |                 for j in lower..upper {
18 | |                     let x: f64 = (f64::from(j) + 0.5) * STEP;
19 | |                     *pi_ref += 4.0 / (1.0 + x * x) * STEP;
20 | |                 }
21 | |             });
   | |_____________- argument requires that `pi` is borrowed for `'1`
```

We can only have one mutable borrow at a time, not one per thread.
This effectively makes the data race impossible.

Adding a Mutex

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```
10      let pi: Mutex<f64> = Mutex::new(0.0);
11      thread::scope(|scope| {
12          for i in 0..NUM_THREADS {
13              let lower: u32 = THREAD_STEPS * i;
14              let upper: u32 = THREAD_STEPS * (i + 1);
15              let pi_ref: &Mutex<f64> = &pi;
16              scope.spawn(move || {
17                  for j in lower..upper {
18                      let x: f64 = (f64::from(j) + 0.5) * STEP;
19                      *pi_ref.lock().unwrap()
20                          += 4.0 / (1.0 + x * x) * STEP;
21                  }
22              });
23          }
24      });
```

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```
25
26      println!("Pi = {:.10}", pi.lock().unwrap());
27  }
```

```
1  $ ./pi-locked
2  Pi = 3.1415926536
```

A Nicer Solution

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```
9       let pi: f64 = thread::scope(|scope| {
10          let mut guards = Vec::new();
11          for i in 0..NUM_THREADS {
12              let lower: u32 = THREAD_STEPS * i;
13              let upper: u32 = THREAD_STEPS * (i + 1);
14              guards.push(scope.spawn(move || {
15                  (lower..upper)
16                      .map(|j| {
17                          let x: f64 = (f64::from(j) + 0.5) * STEP;
18                          4.0 / (1.0 + x * x) * STEP
19                      })
20                      .sum::<f64>()
21              }));
22          }
23
24          guards.into_iter().map(|t| t.join().unwrap()).sum()
25      });
```

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- borrowing rules impose restrictions making some things impossible to express
- `unsafe` allows some additional things
  - calling functions marked `unsafe`
  - FFI calls
  - dereference arbitrary pointers
- keeps regular language semantics in place
- used to create safe abstractions

Unsafe Rust

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```rust
use std::mem::{self, MaybeUninit};

let data = {
    let mut data: [MaybeUninit<Vec<u32>>; 1000] = unsafe {
        MaybeUninit::uninit().assume_init()
    };

    for elem in &mut data[..] {
        elem.write(vec![42]);
    }

    unsafe { mem::transmute::<_, [Vec<u32>; 1000]>(data) }
};
```

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- The Book
- Rustlings
- Rust by Example

Thank you for your attention. Any questions?

https://babelmonkeys.de/~florob/talks/RC-2025-07-02-rust-intro.pdf