
Intro to Rust Lang
Parallelism

# Today: Parallelism

- Parallelism
  - Workers, Processes, and Threads
  - Multithreading
- Mutual Exclusion and `Mutex<T>`
- Atomics
- Message Passing
- `thread::scope`
- `Arc<T>`

# Parallelism vs Concurrency

## Concurrency

**Problem** of handling many tasks at once

## Parallelism

**Solution** of working on multiple tasks at the same time

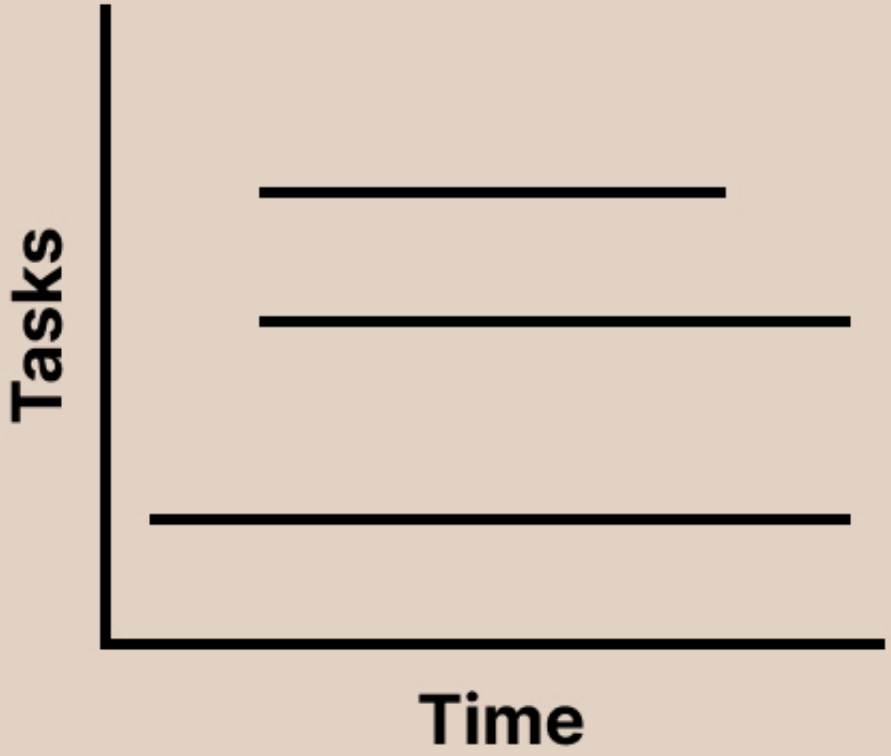
- **Key difference:** Parallelism utilizes **multiple** workers

# Workers

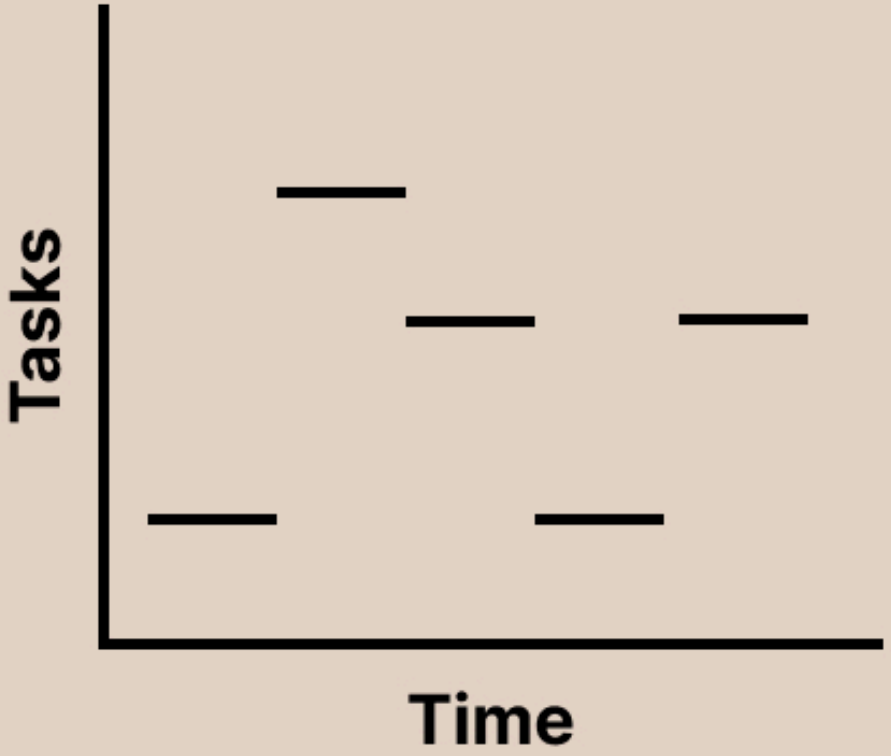
Parallelism divides tasks among workers.

- In hardware, we call these workers **processors** and **cores**
- In software, workers are abstracted as **processes** and **threads**
  - Processes contain many threads
- Parallelism requires **multiple** workers
  - Concurrency models can have any number of workers!

## Parallelism




## Concurrency



# Designing Parallel Solutions

There are two important questions we need to ask:

- Division of labour
  - Who are the workers and how do we divide the work?
- Thread communication
  - What information needs to be shared and how?
    - Approach 1: Shared Memory
    - Approach 2: Message Passing

# Multithreading

For today, we will simplify terminology (that tends to get overloaded).

- Our workers are *threads*
- You can think of threads as a "stream of instructions"

# The Main Thread

The thread that runs by default is the main thread.

```
fn main() {
    for i in 1..3 {
        println!("Main thread says: Hello {i}!");
        thread::sleep(Duration::from_millis(1));
    }
}
```

- So far, we have only been running code on the main thread!

# Spawning a Thread

We can create (spawn) more threads using `std::thread::spawn`.

```
fn main() {
    let child_handle = thread::spawn(|| {
        for i in 1..=8 {
            println!("Child thread says: Hello {i}!");
            thread::sleep(Duration::from_millis(1));
        }
    });

    for i in 1..=3 {
        println!("Main thread says: Hello {i}!");
        thread::sleep(Duration::from_millis(1));
    }
}
```

# Spawning a Thread

```
let child_handle = thread::spawn(|| {
    for i in 1..=8 {
        println!("Child thread says: Hello {i}!");
        thread::sleep(Duration::from_millis(1));
    }
});

for i in 1..=3 {
    println!("Main thread says: Hello {i}!");
    thread::sleep(Duration::from_millis(1));
}
```

- `thread::spawn` takes an `FnOnce` closure
  - The closure will be run on the newly-created thread
- Question: What should this program's output be?

# Possible Output 1

Here is one possible program output:

```
Main thread says: Hello 1!
Child thread says: Hello 1!
Child thread says: Hello 2!
Main thread says: Hello 2!
Child thread says: Hello 3!
Main thread says: Hello 3!
Child thread says: Hello 4!
Child thread says: Hello 5!
```

# Possible Output 2

Here is another possible program output:

```
Main thread says: Hello 1!
Child thread says: Hello 1!
Main thread says: Hello 2!
Main thread says: Hello 3
```

# Possible Output 3

And here is yet another possible program output!

```
Main thread says: Hello 1!
Child thread says: Hello 1!
Main thread says: Hello 2!
Child thread says: Hello 2!
Main thread says: Hello 3!
Child thread says: Hello 3!
```

- What's going on here?

# Multithreaded Code is Non-Deterministic

- Most of the code we have written this semester has been deterministic
- The only counterexamples have been when we've used random number generators or interacted with I/O
- The execution of multi-threaded code can interleave with each other in undeterminable ways!

# Multithreaded Code is Non-Deterministic

In this example, the child thread can interleave its prints with the main thread.

```
let child_handle = thread::spawn(|| {
    for i in 1..=8 {
        println!("Child thread says: Hello {i}!");
        thread::sleep(Duration::from_millis(1));
    }
});

for i in 1..=3 {
    println!("Main thread says: Hello {i}!");
    thread::sleep(Duration::from_millis(1));
}
```

- Why doesn't the child thread print `"Hello"` 8 times?

# Process Exit Kills Threads

- When the main thread finishes execution, the process it belongs to exits
- Once the process exits, all threads in the process are killed
- If we want to let our child threads finish, we have to wait for them!

# Joining Threads

We can `join` a thread when we want to wait for it to finish.

```
// Spawn the child thread.
let child_handle = thread::spawn(|| time_consuming_function());

// Run some code on the main thread.
main_thread_foo();

// Wait for the child thread to finish running.
child_handle.join().unwrap();
```

- `join` will block the calling thread until the child thread finishes
  - In this example, the calling thread is the main thread

# Joining Threads

If we go back to our original example and add a `join` on the child's handle at the end of the program, then the child thread can run to completion!

```
Main thread says: Hello 1!
Child thread says: Hello 1!
Main thread says: Hello 2!
Child thread says: Hello 2!
Child thread says: Hello 3!
Main thread says: Hello 3!
Child thread says: Hello 4!
Child thread says: Hello 5!
Child thread says: Hello 6!
Child thread says: Hello 7!
Child thread says: Hello 8!
```

# Example: Multithreaded Drawing

Suppose we're painting an image to the screen, and we have eight threads.

How should we divide up the work between the threads?

- Divide image into eight regions
- Assign each thread to paint one region
- Easy! "Embarrassingly parallel"
    - Threads don't need to keep tabs on each other

# Example: Multithreaded Drawing

What if our image is more complex?

- We could be painting semi-transparent circles
- Circles could overlap and/or could be constantly moving
- The *order* in which we paint circles changes what we need to draw

# The Case for Communication

If we want consistent drawings, we need a way for our threads to talk / communicate with each other!

- For each pixel:
  - Which color circle should it draw?
  - How many circles have been drawn on this pixel?
  - Do we need to wait for other circles to finish being drawn?
- Simplification for today: each pixel tracks how many circles it has to draw

# Motivating Communication

**Problem:** How do threads communicate?

**Solutions:** We'll discuss two approaches...

- Approach 1: Shared Memory
- Approach 2: Message Passing

# Approach 1: Shared Memory

For each pixel, create a shared variable `x` that represents the number of circles that overlap on this pixel:

```
static int x = 0; // One per pixel.
```

- *Note that this is C pseudocode: we'll explain the Rust way soon*
- When a thread touches a pixel, increment the pixel's associated `x`
- Now each thread knows how many layers of paint there are on that pixel

# Approach 1: Shared Memory

Are we done?

- Not quite...
- Shared memory is prone to **data races**

# Shared Memory: Data Races

**Step 1:** `x` is in shared memory, and `x` must uphold some invariant to be correct.

```
// Invariant: `x` is total number of times **any** thread has called `update_x`.
static int x = 0;

static void update_x(void) {
    x += 1;
}
```

# Shared Memory: Data Races

**Step 2:** `x` temporarily becomes incorrect (mid-update).

```
// Invariant: `x` is total number of times **any** thread has called `update_x`.
static int x = 0;

static void update_x(void) {
    int temp = x;   // `x` lags the number of times `update_x` has been called by 1.
    temp += 1;      // `x` is still incorrect...
    x = temp;       // `x` is now correct!
}
```

- We don't actually write code like this
  - This is how it gets compiled to machine instructions

# Shared Memory: Data Races

**Step 3**: Multiple threads update `x` at the same time...

```
// Invariant: `x` is total number of times **any** thread has called `update_x`.
static int x = 0;

static void update_x(void) {
    x += 1;
}

// <!-- snip -->

for (int i = 0; i < 20; ++i) {
    spawn_thread(update_x);
}
```

# Shared Memory: Data Races

**Step 3**: When multiple threads update `x` at the same time... they interleave!

| Thread 1 | Thread 2 |
|---|---|
| `temp = x` | |
| | `temp = x` |
| `temp += 1` | |
| | `temp += 1` |
| `x = temp` | |
| | `x = temp` |

# Shared Memory: Data Races

We want `x = 2`, but we could get `x = 1`!

| Thread 1 | Thread 2 |
| --- | --- |
| Read `temp = 0` | |
| | Read `temp = 0` |
| Set `temp = 1` | |
| | Set `temp = 1` |
| Set `x = 1` | |
| | Set `x = 1` |

# Shared Memory: Atomicity

We want the update to be **atomic**. That is, other threads cannot cut in mid-update.

### Not Atomic

| Thread 1 | Thread 2 |
|---|---|
| `temp = x` | |
| | `temp = x` |
| `temp += 1` | |
| | `temp += 1` |
| `x = temp` | |
| | `x = temp` |

### Atomic

| Thread 1 | Thread 2 |
|---|---|
| `temp = x` | |
| `temp += 1` | |
| `x = temp` | |
| | `temp = x` |
| | `temp += 1` |
| | `x = temp` |

# Fixing a Data Race

We must eliminate one of the following:

1. `x` is in shared memory
2. `x` temporarily becomes incorrect (mid-update)
3. Unsynchronized updates (parties can "cut in" mid-update)

# Mutual Exclusion

# Approach 1: Mutual Exclusion

Take turns! No "cutting in" mid-update.

1. `x` is in shared memory
2. `x` temporarily becomes incorrect (mid-update)
3. ~~Unsynchronized updates (parties can "cut in" mid-update)~~

# Approach 1: Mutual Exclusion

We need to establish *mutual exclusion*.

- You can think of mutual exclusion as "Only one thread at a time"
  - Mutual exclusion means threads don't interfere with each other
- A common tool for this is a `mutex` lock

# Mutual Exclusion in C

Here is how you would use a `mutex` in C:

```
static int x = 0;
static mutex_t x_lock;

static void run_thread(void) {
    mtx_lock(&x_lock);
    x += 1;
    mtx_unlock(&x_lock);
}
```

- Only one thread can hold the mutex lock ( `mutex_t` ) at a time
- Other threads block / wait until they get their turn to hold the lock
- Each thread gets "mutual exclusion" over `x`

# Mutual Exclusion in Rust

In Rust, the `Mutex` exists in the standard library!

```
use std::sync::Mutex;

// Details incoming in a few slides...
fn main() {

    let m: Mutex<i32> = Mutex::new(42);

    {
        let mut num = m.lock().unwrap();
        *num += 1;
    }

    println!("m = {:?}", m);
}
```

# `Mutex<T>`

Rust's `Mutex` is a smart pointer!

- `Mutex<T>` owns the data it protects
  - In C, you as the programmer have to ensure the mutex is locked correctly
  - In Rust, you cannot access the data unless you hold the lock!
- Rust can achieve this using a `MutexGuard<'a, T>`
  - You can think of a `Mutex` as the lock provider and the `MutexGuard` as the lock itself

# `MutexGuard<'a, T>`

The `MutexGuard<'a, T>` created from the `Mutex<T>` is also a smart pointer!

```
let m: Mutex<i32> = Mutex::new(42);
{
    // Create a `MutexGuard` that gives the current thead exclusive access.
    let guard1 = m.lock().expect("lock was somehow poisoned");

    // Dereference the guard to get to the data.
    let num = *guard1;
    println!("{num}");
}
// At the end of the scope, `guard1` gets dropped and the lock is released.

// Since the first guard was dropped, we can take the lock again!
let guard2 = m.lock().expect("lock was somehow poisoned");
```

- *Ask us after lecture if you're interested in why there is a lifetime there...*

# `Mutex::lock`

Here is the signature for `Mutex::lock`:

```
pub fn lock(&self) -> LockResult<MutexGuard<'_, T>> {}
```

- Do you notice anything strange about this?
- Remember that you are able to *mutate* the data once you have the guard

# Interior Mutability

```
pub fn lock(&self) -> LockResult<MutexGuard<'_, T>> {}
```

- This allows multiple workers to access the lock without a mutable reference
- Even though `lock` takes an *immutable* reference, we are allowed to *mutate* the data that the guard is protecting
- We call this *interior mutability*
- More experienced rustaceans call references "shared" and exclusive" instead of "immutable" and "mutable" for this exact reason

# Atomics

# Approach 2: Atomics

One airtight, *atomic* update! Cannot be "temporarily incorrect" mid-update.

1. `x` is in shared memory
2. ~~`x` temporarily becomes incorrect (mid-update)~~
3. Unsynchronized updates (parties can "cut in" mid-update)

# Code to Machine Instructions

Recall that the compiler will usually translate the following operation...

```
x += 1;
```

...into the machine instruction equivalent of this code:

```
int temp = x;
temp += 1;
x = temp;
```

# Atomics

However, we can use an atomic operation like this:

```
__sync_fetch_and_add(&x, 1); // syntax depends on library
```

...which is implemented in hardware with just one instruction:

```
x += 1;
```

- `fetch_and_add`: performs the operation suggested by the name, and returns the value that was previously in memory
  - Also `fetch_and_sub`, `fetch_and_or`, `fetch_and_and`, ...

## Aside: `compare_and_swap`

Another common atomic operation is `compare_and_swap`

- If the current value matches an old value, update the value
  - Returns whether or not the value was updated
- You can do "lock-free" programming with just CAS
  - No locks! Just `compare_and_swap` until we successfully write new value
    - *Not necessarily more performant than lock-based solutions*

# Atomics

These atomic operations are also implemented in the Rust standard library.

```
use std::sync::atomic::{AtomicI32, Ordering};

let x = AtomicI32::new(0);

x.fetch_add(10, Ordering::Relaxed);
x.fetch_sub(2, Ordering::AcqRel);

println!("Atomic Output: {}!", x.load(Ordering::SeqCst));
```

```
Atomic Output: 8!
```

# Atomics

```
let x = AtomicI32::new(0);

x.fetch_add(10, Ordering::Relaxed);
x.fetch_sub(2, Ordering::AcqRel);

println!("Atomic Output: {}!", x.load(Ordering::SeqCst));
```

- The API is largely identical to C++20 atomics
- If you're interested in what the `Ordering` is, look up "memory ordering"

# Atomic Action

Here is an example of incrementing an atomic counter from multiple threads!

```
static counter: AtomicUsize = AtomicUsize::new(0);

fn main() {
    // Spawn 100 threads that each increment the counter by 1.
    let handles: Vec<JoinHandle<_>> = (0..100)
        .map(|_| thread::spawn(|| counter.fetch_add(1, Ordering::Relaxed)))
        .collect();

    // Wait for all threads to finish.
    handles.into_iter().for_each(|handle| { handle.join().unwrap(); });

    assert_eq!(counter.load(Ordering::Relaxed), 100);
}
```

# Message Passing

# Eliminating Shared Memory

If we eliminate shared memory...

1. ~~`x` is shared memory~~
2. `x` becomes incorrect mid-update
3. Unsynchronized updates

# Eliminating Shared Memory

If we eliminate shared memory... any data races are trivially gone.

1. ~~`x` is shared~~
2. ~~`x` becomes incorrect mid-update~~
3. ~~Unsynchronized updates~~

# Message Passing

Now we'll talk about the second approach to communication, message passing!

- Approach 1: Shared Memory
- Approach 2: Message Passing
  - **Eliminates shared memory**

# Message Passing

- Threads communicate via *channels*
  - You can think of a sending thread sending a message down a river
  - Receiving thread picks up the message downstream
- Popular mechanism for concurrency and synchronization in the Go language

# Creating channels

Channels consist of both a transmitter and a receiver.

```
let (tx, rx) = mpsc::channel();
```

- **Transmitter**: Connor writes "Review the ZFOD PR" and sends it down a river
- **Receiver**: Ben finds the duck downstream and reads the message
- Each channel can only transmit/receive one type
- Communication is only one-way
- This is an `mpsc`-flavored channel...

# Message Passing Example

Here's an example of a child thread sending a message to the main thread.

```
let (tx, rx) = mpsc::channel();

thread::spawn(move || { // Takes ownership of `tx`.
    let val = String::from("review the ZFOD PR!");
    tx.send(val).unwrap(); // Send `val` through the transmitter.
});

let received = rx.recv().unwrap(); // Receive `val` through the receiver.
println!("I am too busy to {}!", received);
```

- After we send `val`, we no longer have ownership of it

# Message Passing Iterator

We can also use receivers as iterators!

```
let (tx, rx) = mpsc::channel();

thread::spawn(move || { // Takes ownership of `tx`.
    let val = String::from("review the ZFOD PR!");

    tx.send(val).unwrap(); // Send `val` through the transmitter.
    tx.send("buy Connor lunch".into()).unwrap(); // Send another message!
});

for msg in rx { // Iterate through messages until all transmitters are dropped.
    println!("I am too busy to {}!", msg);
}
```

- Wait, what does `mpsc` stand for?

# `mpsc` ⟹ Multiple Producer, Single Consumer

This means we can `clone` the transmitter to get *multiple message producers*.

```
let (tx, rx) = mpsc::channel();

let tx_clone = tx.clone();
thread::spawn(move || { // Takes ownership of `tx_clone`.
      tx_clone.send("yo".into()).unwrap();
      thread::sleep(Duration::from_secs(1));
});

thread::spawn(move || { // Takes ownership of `tx`.
      tx.send("hello".into()).unwrap();
      thread::sleep(Duration::from_secs(1));
});
```

# Parallelism in Rust

# Threads in Rust

Rust uniquely provides some nice guarantees for parallel code, and at the same time introduces a few complications...

- Rust's typechecker guarantees an absence of *any data races*
  - Unless you use `unsafe`
  - This is a super powerful guarantee!
- General race conditions are not prevented (non-determinism)
  - Deadlocks are still possible

# Creating Threads: Detailed

Recall that threads can be spawned with `thread::spawn`.

```
let child_handle = thread::spawn(|| {
    for i in 1..=8 {
        println!("Child thread says: Hello {i}!");
        thread::sleep(Duration::from_millis(1));
    }
});
```

- `thread::spawn` takes in a closure, implementing the `FnOnce` and `Send` traits
  - `FnOnce` implies we cannot spawn multiple threads of the same closure
  - `Send` is a marker trait that says the type is safe to send to another thread
    - You can read more about `Send` here in the Rustonomicon

# Capturing Values in Threads

What if we want to use a value from outside the closure?

```
let v = vec![1, 2, 3];

thread::spawn(|| {
    println!("Here's a vector: {:?}", v);
});
```

# Capturing Values in Threads

```
error[E0373]: closure may outlive the current function, but it borrows `v`, which is owned by the current function
 --> src/main.rs:6:19
  |
6 |     thread::spawn(|| {
  |                   ^^ may outlive borrowed value `v`
7 |         println!("Here's a vector: {:?}", v);
  |                                           - `v` is borrowed here
  |

note: function requires argument type to outlive `'static`
 --> src/main.rs:6:5
  |
6 | /     thread::spawn(|| {
7 | |         println!("Here's a vector: {:?}", v);
8 | |     });
  | |______^

help: to force the closure to take ownership of `v` (and any other referenced variables), use the `move` keyword
  |
6 |     thread::spawn(move || {
  |                   ++++
```

- In other words, what if `v` goes out of scope while the thread is still running?

# Moving Values into Threads

To solve this, we can take ownership of values by *moving* them into the closure.

```
let v = vec![1, 2, 3];

let handle = thread::spawn(move || {
    println!("Here's a vector: {:?}", v);
});
```

# Access from Different Threads

What if we want `v` to remain accessible in the main thread?

```
fn main() {
    let v = vec![1, 2, 3];

    thread::spawn(move || {
        println!("Vector from child: {:?}", v);
    });

    // THIS DOESN'T COMPILE!
    println!("Vector from parent: {:?}", v);
}
```

# Access from Different Threads

- We could clone `v` to keep it accessible in the main thread
  - But cloning can be expensive
  - And what if we actually want to share `v` between the threads?
- There are at least two alternatives to cloning here:
  - Approach 1: `thread::scope`
  - Approach 2: `Arc` and `Mutex`

# Local Data?

Suppose we're writing a function to process a large array in parallel:

```
fn main() {
    let mut data = [1, 2, 3, 4, 5, 6]; // Pretend this is much larger...
    compute_squares(data);
}
```

- The array is local to the function (stack-allocated)
  - We don't want to move ownership
  - We don't want to allocate it on the heap unnecessarily

# Approach 1: `thread::scope`

`thread::scope` creates a scope for spawning threads that *borrows* local data.

```
fn compute_squares(numbers: &mut [i32]) {
    thread::scope(|s| {
        let mid = numbers.len() / 2;
        let (left, right) = numbers.split_at_mut(mid);

        let t1 = s.spawn(/* do stuff with `left` */);
        let t2 = s.spawn(/* do stuff with `right` */);
    });
}
```

- `thread::scope`'s closure takes a `Scope` object `s`
  - You use this `s` to spawn threads with `s.spawn`

# Approach 1: `thread::scope`

Threads are joined automatically when the scope exits

```
fn compute_squares(numbers: &mut [i32]) {
    thread::scope(|s| {
        let mid = numbers.len() / 2;
        let (left, right) = numbers.split_at_mut(mid);

        let t1 = s.spawn(/* do stuff with `left` */);
        let t2 = s.spawn(/* do stuff with `right` */);
    });
}
```

- No explicit `join` is needed
  - Very clean!

# Approach 1: `thread::scope`

The Rust compiler ensures that the borrowed data ( `numbers` ) outlives all threads.

```
fn compute_squares(numbers: &mut [i32]) {
    thread::scope(|s| {
        let mid = numbers.len() / 2;
        let (left, right) = numbers.split_at_mut(mid);

        let t1 = s.spawn(/* do stuff with `left` */);
        let t2 = s.spawn(/* do stuff with `right` */);
    });

    // Can still access `numbers`!
    println!("Finished computing squares: {:?}", numbers);
}
```

# Multiple Thread Access

- With `thread::scope`, we can share local data across threads
- What if we actually wanted different threads to access and own the data?

# Multiple Thread Access

Let's say we want two threads to access a mutex-protected vector.

```
let data = Mutex::new(vec![2, 3, 4, 5]);

let t1 = thread::spawn(|| {
    let mut data_guard = data.lock().unwrap();
    data_guard.insert(0, 1);
});
let t2 = thread::spawn(|| {
    let mut data_guard = data.lock().unwrap();
    data_guard.push(6);
});
```

# Multiple Thread Access

```
error[E0373]: closure may outlive the current function, but it borrows
              `data`, which is owned by the current function
  --> src/main.rs:7:28
   |
7  |     let t1 = thread::spawn(|| {
   |                            ^^ may outlive borrowed value `data`
8  |         let mut data_guard = data.lock().unwrap();
   |                              ---- `data` is borrowed here
   |
help: to force the closure to take ownership of `data` (and any other
      referenced variables), use the `move` keyword
   |
7  |     let t1 = thread::spawn(move || {
   |                            ++++
```

# Multiple Thread Access

- We can't access the local Mutex from the child threads because the parent thread might finish first
- We also cannot `move` the mutex into both threads (can only move into one)
- What we really want is for both threads to *own* the data
  - This should remind you of `Rc<T>`!

# Remember `Rc<T>`?

Recall the `Rc<T>` (Reference Counted) Smart Pointer.

- `Rc<T>` points to a heap-allocated value
  - Keeps track of the number of references to the value (refcount)
  - The data is dropped when the reference count hits zero
- Provides **shared ownership** of the value

# `Rc<T>`

But, `Rc<T>` is not thread-safe... updates to the reference count are not atomic!

| Thread 1 | Thread 2 |
| --- | --- |
| `temp = refcount` | |
| | `temp = refcount` |
| `temp += 1` | |
| | `temp += 1` |
| `refcount = temp` | |
| | `refcount = temp` |

# `Arc<T>`

`Rc<T>` has an equivalent atomic version `Arc<T>`.

- "**A**tomically **R**eference **C**ounted"
- Same functionality as `Rc<T>`, but thread-safe
  - Reference count is atomically updated
- Use `Rc<T>` for single-threaded operations, `Arc<T>` for multi-threaded

# Approach 2: `Arc<Mutex<T>>`

Here is the other approach, using `Arc<T>` and `Mutex<T>`.

```
let data = Arc::new(Mutex::new(vec![2, 3, 4, 5]));
let data_clone = Arc::clone(&data);

let t1 = thread::spawn(move || {
    let mut data_guard = data.lock().unwrap();
    data_guard.insert(0, 1);
});
let t2 = thread::spawn(move || {
    let mut data_guard = data_clone.lock().unwrap();
    data_guard.push(6);
});
```

- Both threads own the mutex!

# Approach 2: `Arc<Mutex<T>>`

Here is a more practical application of `Arc<Mutex<T>>`:

```
let data = Arc::new(Mutex::new(vec![]));

for i in 0..10 {
    let data = data.clone();
    handles.push(thread::spawn(move || {
        let mut guard = data.lock().expect("lock was somehow poisoned");
        guard.push(i);
    }));
}

// Code for joining handles and printing omitted.
```

```
[1, 0, 3, 6, 5, 4, 2, 7, 9, 8]
```

# `Send` and `Sync`

- `Send` and `Sync`: **marker traits** used to enforce safety with multiple threads
  - `Send`: indicates that `T` can be safely sent between threads
  - `Sync`: indicates that `T` can be safely referenced between threads
    - *Only if `&T` implements `Send`

# Other Synchronization Primitives

There are shared state **primitives** other than `Arc<T>` and `Mutex<T>`:

- `RwLock<T>`: a lock which can have concurrent *readers*
- `CondVar<T>`: blocks a thread until a condition is met
- `Barrier`: memory barrier where threads can wait for others to reach it
- and more...

# Review: "Fearless Concurrency"

Today's content is referred to as "fearless concurrency" in the Rust community:

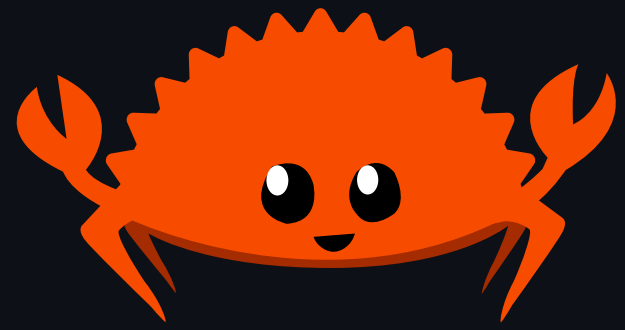
- By leveraging Rust's type system, we can move entire classes of concurrency and parallelism bugs to compile-time
- Rather than choosing a restrictive "dogmatic" approach to concurrency, Rust supports many different approaches, all of which are completely safe
- Some people believe that this may be the *best reason* to use Rust

# Final Homework: The Billion Row Challenge

- Process a billion rows as fast as possible!
- The key objective is to learn to optimize a program by applying parallelism in Rust
- Feel free to use 3rd-party crates (Rayon should be a useful one)
- Have fun 😄

# Next Lecture: Concurrency

Thanks for coming!



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