Concurrent programming in Rust

4SE05

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Outline

Concurency in Rust

Why use Rust

> *For example, introducing parallelism in Rust is a relatively low-risk operation: the compiler will catch the classical mistakes for you.*
>
> *— The rust book, foreword*

> *By leveraging ownership and type checking, many concurrency errors are compile-time errors in Rust rather than runtime errors.*
>
> *— The rust book, chapter 16*

Two types of concurrency

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- Threaded concurrency
  - Based on threads, like in C
  - Good for compute-bound workloads,
- Asynchronous concurrency
  - Based on futures / promise / task / async functions
  - Seen in Python, JavaScript/TypeScript
  - Good for IO-bound workloads,
  - Used in embassy (cf 4SE02)

Concurency in Rust

Safty guarantiees in Rust

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Sharing value with `Rc`

`Rc` is a smart pointer.

It can be cloned, and count the number of time was cloned.

It allow for an value to have a lifetime long enough for all the time it is used.

```
fn rc_to_thread() {
    let a = Rc::from(1);
    let b = a.clone();
    let j = spawn(move || println!("val = {}", *b));
    j.join();
}
```

Sharing value with Rc, errors!

```
error[E0277]: `Rc<i32>` cannot be sent between threads safely
   --> src/main.rs:90:19
    |
90  |     let j = spawn(move || println!("val = {}", *b));
    |             ----- -------^^^^^^^^^^^^^^^^^^^^^^^^^
    |             |     |
    |             |     `Rc<i32>` cannot be sent between threads safely
    |             |     within this `{closure@src/main.rs:90:19: 90:26}`
    |             required by a bound introduced by this call
    |
   = help: within `{closure@src/main.rs:90:19: 90:26}`, the trait `Send`
is not implemented for `Rc<i32>`
```

The `Send` and `Sync` trait

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The compiler implements those trait when possible :

`Send` The value can be moved between threads.

`Sync` Reference to the value can be moved between threads.

Sharing value with `Arc`

To share the ownership of a value of type `T` across threads boundaries, you might use `Arc<T>` instead of `Rc<T>`.

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Here the counter is atomic, so the compiler add the `Send` trait and the `Arc` can be moved between threads.

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Here the counter is atomic, so the compiler add the `Send` trait and the `Arc` can be moved between threads.

Shared ownership does not permit mutability, `Arc` can only be deref into inmutable reference.

Primitives

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  - thread
  - sync
    - mutex
    - channel
  - future
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You can build more complex primitives from basic primitives, or using unsafe block.

Atomics

Atomics lives in `std::sync::atomics`.

```
use std::sync::atomic::{AtomicU16, Ordering};

let atomic = AtomicU16::new(0);
assert_eq!(atomic.load(Ordering::Relaxed), 0);
atomic.store(1, Ordering::Relaxed);
assert_eq!(atomic.fetch_add(10, Ordering::Relaxed), 1);
assert_eq!(atomic.swap(100, Ordering::Relaxed), 11);
assert_eq!(atomic.load(Ordering::Relaxed), 100);
```

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

The ordering is the same as in C++ 20

Atomics : Ordering

`Relaxed`: only guarantee atomicity and modification order consistency,

`AcqRel`: also, things that append before/after a store in one threads append before/after a read in another thread,

`SeqCst`: also, there is a single total modification order of all atomic operations that are so tagged

Atomics : Creating a mutex

```
pub struct SpinLockMutex{
    locked : AtomicBool,
}
impl SpinLockMutex {
    pub fn new() -> Self{
        SpinLockMutex { locked: AtomicBool::new(false) }
    }
    pub fn lock(&self) -> (){
        loop {
            let old_state = AtomicBool::swap(&self.locked, true, Ordering::AcqRel);
            if !old_state {return;}
        }
    }
    pub fn unlock(&self) -> (){
        AtomicBool::store(&self.locked, false, Ordering::AcqRel);
    }
}
```

Interior Mutability

```rust
let atomic = AtomicU16::new(0);

pub fn swap(&self, val: bool, order: Ordering) -> bool
pub fn lock(&self) -> ()
pub fn unlock(&self) -> ()
```

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```

In Rust, some type allows its value to be mutated even on not mutable instances.

Interior Mutability with `Cell`

`Cell<T>` is a container used to create interior mutability.

```
pub fn set(&self, val: T)
pub fn replace(&self, val: T) -> T
pub fn swap(&self, other: &Cell<T>)
```

`Cell` is not `Send` : it is not atomic from other threads, only from its own thread.

Concurrent primitive for threaded concurrency

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Threads

Thread model

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- If another thread panics, nothing happens.
- If the main thread terminates before the other, the other threads are stopped.

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```
let mut x = 0;
let add = |y| {x + y}; //Fn
let mut inc_by = |y| {x += y}; //FnMut

x: String = String::from("Léopold");
let concat_to_x = |y: String| add(x, &y); //FnOnce
                                          // x is consumed by add
```

Spawning and joining a thread

```rust
let t = std::thread::spawn(move || {
    println!("Hi from the thread");
});
println!("Hi from main");
t.join().unwrap();
```

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```

Always `join` a thread.

Move value inside threads, wrong

```
let name = Arc::new("Leopold");
let hello_from_inside =|x:usize, name| {println!("Hi {} from {}", name,
x);};
let t1 = spawn(move || hello_from_inside(1, name));
let t2 = spawn(move || hello_from_inside(2, name));
```

```
error[E0382]: use of moved value: `name`
```

Move value inside threads, correct

Il faut cloner explicitement les `Arc`

```
    let name = Arc::new("Leopold");
    let hello_from_inside =|x:usize, name| {println!("Hi {} from {}",
name, x);};
    let tmp = name.clone(); // clone the Arc
    let t1 = spawn(move || hello_from_inside(1, tmp)); //tmp move, not
name
    let tmp = name.clone();
    let t2 = spawn(move || hello_from_inside(2, tmp));
```

Communication between threads

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- Shared state
  - use `mutex`
  - every threads can read/write
- Message passing
  - use `channel`
  - some threads are writer, some are reader

Concurrent primitive for threaded concurrency

Mutex

Usecase

A `mutex` allow to share a value between thread. Only one thread may access the value at a time.

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A `mutex` allow to share a value between thread. Only one thread may access the value at a time. In Rust, `Mutex` is a wrapper around a non-atomic value. Each thread has a reference to the `Mutex`, but only on at a time has a reference to the value.

Lifecycle of a Mutex

```
let mut threads : Vec<JoinHandle<_>> = Vec::new();
let counter = Arc::new(Mutex::new(0));
for idx_thread in 0..N_MAX{
    let counter = counter.clone();
    threads.push(spawn(move || {
        for _ in 0..idx_thread{
            let mut c = counter.lock().unwrap();
            *c += 1;}
      }));
    }
for t in threads.into_iter(){t.join().unwrap();}
assert_eq!(*counter.lock().unwrap(), (N_MAX-1)*(N_MAX)/2);
```

Taking a Mutex

```
fn lock(&self) -> LockResult<MutexGuard<'_, T>>;
fn try_lock(&self) -> TryLockResult<MutexGuard<'_, T>>;

LockResult<T> = Result<T, PoisonError<T>>;
TryLockResult<T> = Result<T, TryLockError<T>>;
```

The mutex might be poisoned, and can’t be taken.

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There are two interfaces :

- blocking : `lock`
- non-blocking : `try_lock`

Releasing a Mutex

The mutex is released a the end of the context where it was locked.

You can also use `std::mem::drop`.

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You can also use `std::mem::drop`.

```
for _ in 0..idx_thread{
  let mut c = counter.lock().unwrap();
  *c += 1;
  } // counter is released here
```

Poisoned Mutex

If a thread panic while holding a mutex, the mutex will be poisoned. A poisoned mutex can not be taken by anyone.

A mutex can be tested for poison with `is_poisoned` and cured with `clear_poison`. This only affect the mutex, the inner data might still be corrupted.

Concurrent primitive for threaded concurrency

Channel `mpsc`

Usecase

A `Channel` allow to pass messages between context.

The base implementation allow multiple writer and one reader. The channel has an infinite capacity.

Creating a channel

A channel for value of type `T` is represented by its ends, the `Sender<T>` (`tx`) and the `Receiver<T>` (`rx`).

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

The `Sender` can be cloned, to create multiple producer.

Sending through the channel

```
fn send(&self, t: T) -> Result<(), SendError<T>>
```

Return an error only if the `rx` is dropped. `Ok` doesn’t mean that the message is received. This will never block.

Receiving through the channel

```
fn recv(&self) -> Result<T, RecvError>
```

Will block if no message in the channel. Will return an `Err` if the `Sender` is disconnected.

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There is a non-clocking interface, `try_recv` and a timout interface `recv_timeout`.

```
fn recv_timeout(&self, timeout: Duration) -> Result<T, RecvTimeoutError>
fn try_recv(&self) -> Result<T, TryRecvError>
```

Receiving through the channel

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fn recv_timeout(&self, timeout: Duration) -> Result<T, RecvTimeoutError>
fn try_recv(&self) -> Result<T, TryRecvError>
```

The `Receiver` can also be turned into a iterator:

```
for msg in rx.iter() {
  ...
}
```

Async/await, `Future` and cooperative concurrence

Async/await, `Future` and cooperative concurrence

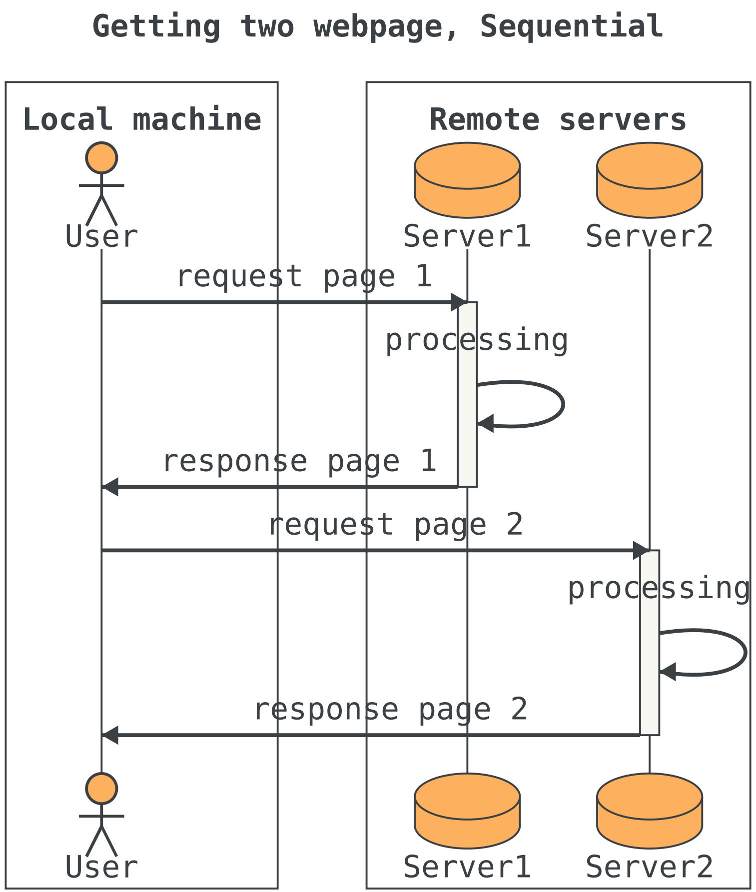
Getting two pages at the same time

Problem stattement

How to get the content of two web page ?

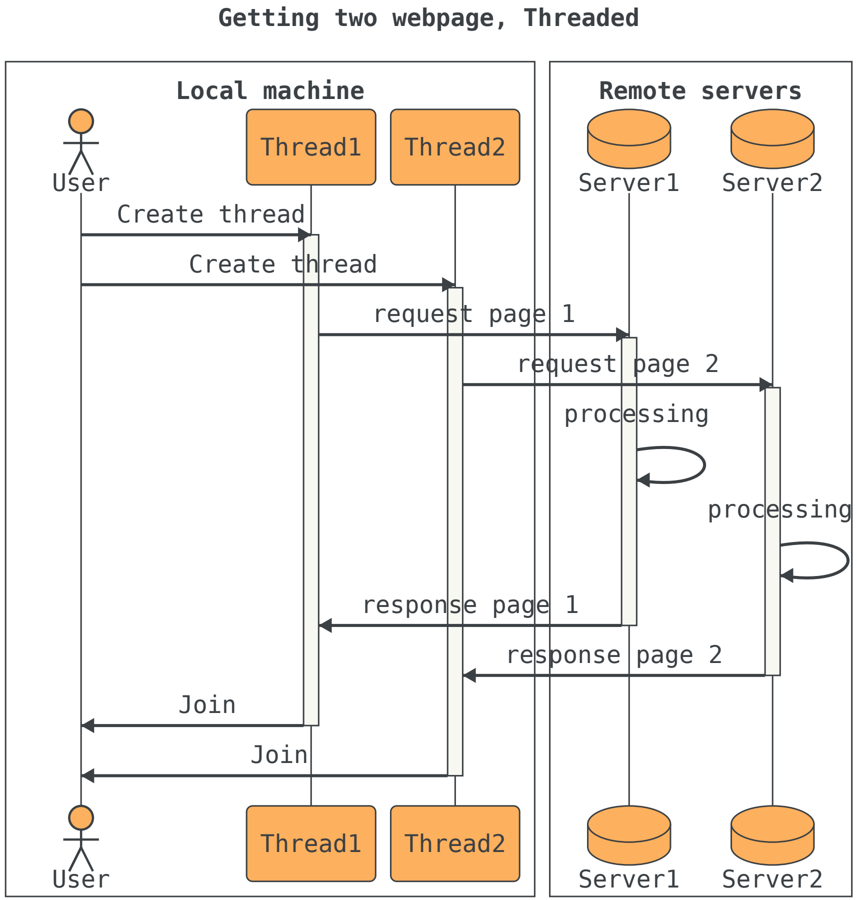
- as fast as possible
- without using too much ressources

Sequential



- simple
- slow
- use only one stack

Threaded



- use the os for context switching
- fast
- use three stacks

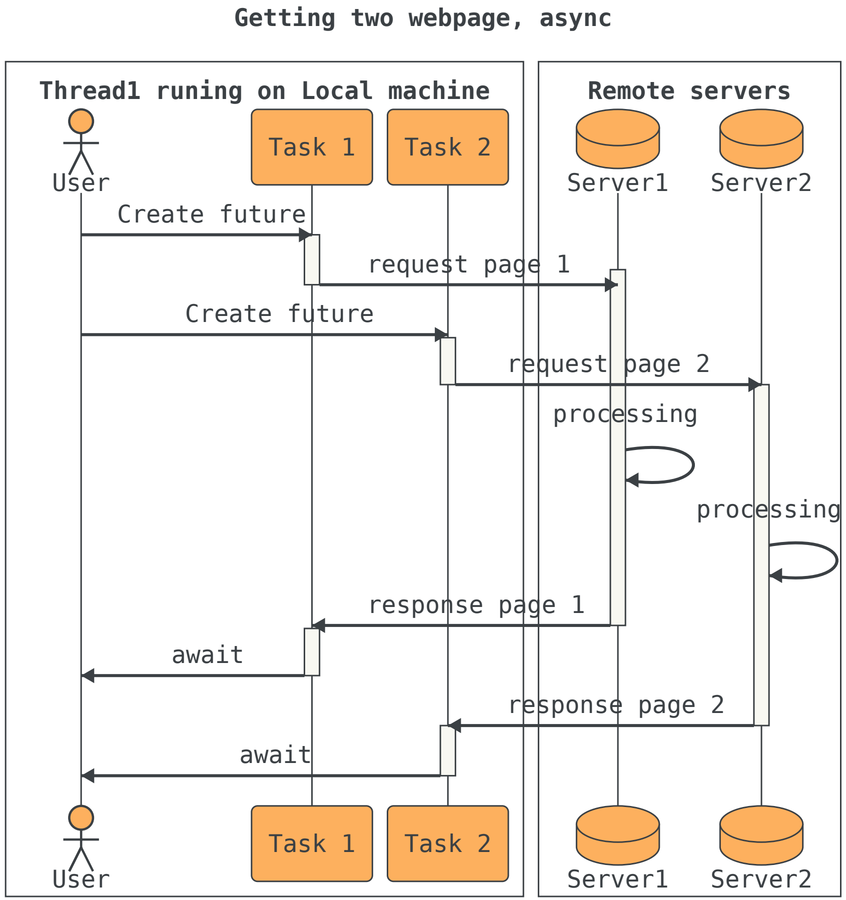
Issue with threads

- Compute vs IO bound:
  - here, we are IO-bound
  - adding compute time through threads is not usefull

Issue with threads

- Compute vs IO bound:
  - here, we are IO-bound
  - adding compute time through threads is not usefull
- Scaling to many tasks:
  - one thread by tasks $\Longrightarrow$ one stack by task $\Longrightarrow$ heavy memory usage
  - could we use only one the main thread and distribute compute time to tasks ?

Asynchronous tasks



- use a local algorithm for context switching
- fast
- use one stack

Task, future, executor

- tasks, and their sub-tasks:
  - are represented as the promise of a future value (that value can be the unit type if ther is no return value)
  - can do a little progress at a time, stoping when they can not progress anymore or are finised
- an algorithm, the executor:
  - run on the main thread
  - distribute compute time at each task

Async/await, `Future` and cooperative concurrence

Implementation in Rust

Futures

```
enum Poll<T> { // core::task::Poll
  Ready(T),
  Pending,
}
trait Future { // core::future::Future
  type Output;
  // Required method
  fn poll(self: Pin<&mut Self>, cx: &mut Context<'_>)
    -> Poll<Self::Output>;
}
```

The context of a task is stored in the other member of the struct. `poll` must be nonblocking.

Resolving a future

- Resolving a future is polling it until it return `Ready`.
- `Future` implementation use a `Waker` to signal that the future is ready to be polled.
  - this allow for task to only wakeup when progress is possible.
- Unlike `Javascript` or `C#`, the task polling is done by the program, not by the runtime/vitual machine.

Implementing `Future`

- `Future` should be implemented as state machine,
- `Future` should not start their work before the first `poll`,
- `Future` should use the `Waker` to be called again,
- if a `Future` contain another `Future`, it should call the `poll` of the children each time it is called,
- `poll` must be quick

A delay future

```
struct Delay {when: Instant}
impl Future for Delay {
    type Output = &'static str;
    fn poll(self: Pin<&mut Self>, cx: &mut Context<'_>)-> Poll<&'static str>
    {   if Instant::now() >= self.when {
            println!("Hello world");
            Poll::Ready("done")
        } else {
            let waker = cx.waker().clone();// Get a handle to the waker
            let when = self.when;
            thread::spawn(move || { // Spawn a timer thread.
                let now = Instant::now();
                if now < when {thread::sleep(when - now);}
                waker.wake();
            });
            Poll::Pending
      }}}
```

Async function

```rust
// fn slow_getter(&str) -> impl Future<i32>;
async fn slow_get_add(r: &str, n: i32) -> i32 {
  let r = get_slow(r).await;
  r + n
}
```

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async fn slow_get_add(r: &str, n: i32) -> i32 {
  let r = get_slow(r).await;
  r + n
}
```

`async` marks the function, the compiler will turn it into the function `fn slow_getter(&str, i32) -> impl Future<i32>`. The associated structure implementiong `Future` will also be generated. The `.await` marks that the future should poll the `get_slow` future.

Multiple Futures to await

```
async fn get_plus_twice_bad(r1: &str, r2: &str, n: i32) -> (i32, i32) {
  let p1 = slow_get_add(r1, n).await;
  let p2 = slow_get_add(r2, n).await;
  (p1, p2)
}
async fn get_plus_twice(r1: &str, r2: &str, n: i32) -> (i32, i32) {
  let pair = join(slow_get_add(r1, n), slow_get_add(r2, n));
  pair.await
}
```

Futures will only start to execute if there are awaited/polled.

Executor

The executor is the object that handle polling the tasks.

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There is no runtime/executor in `std`. The main ones are:

- `Tokio` for hosted environement
  - include io async function for IO (network and filesystem)
  - awaitable synchronisation primitive (mutex, channel)
- `Embassy` for embedded environement
  - include async hardware abstraction layer

Tokio, main task

```rust
#[tokio::main]
async fn main() -> Result<()> {
    let mut client = client::connect("127.0.0.1:6379").await?;

    client.set("hello", "world".into()).await?;

    let result = client.get("hello").await?;

    println!("got value from the server; result={:?}", result);

    Ok(())
}
```

Tokio, creating tasks

```rust
#[tokio::main]
async fn main() -> Result<(), Box<dyn std::error::Error>> {
    let listener = TcpListener::bind("127.0.0.1:8080").await?;
    loop {
        let (mut socket, _) = listener.accept().await?;
        let handle = tokio::spawn(async move {
            let mut buf = [0; 1024];
            loop {// In a loop, read data from the socket and write the data back.
                let n = match socket.read(&mut buf).await {
                    Ok(0) => return, // socket closed
                    Ok(n) => n,
                    Err(e) => {
                        eprintln!("failed to read from socket; err = {:?}", e);
                        return;}};
                if let Err(e) = socket.write_all(&buf[0..n]).await {
                    eprintln!("failed to write to socket; err = {:?}", e);
                    return;
}}});}}
```

When spawned with `spawn`, tasks are eagerly executed.

Good practice for async

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Good practice for async

- No blocking in async functions!
- Do not hold a `mutex` across a `await`,
- use the `join!` macro to await multiple future at the same time.
- use the crate `futures`:
  - the `join` futures to await multiple future at the same time,
  - an awaitable `Mutex`

Conclusion

Threads vs Futures

- Threads
  - Compute-bound program
  - expensive to start
  - can exploit multi-hart computer
  - relies on the OS
  - communication via channel or mutex
  - can block
- Futures
  - IO-bound program
  - cheap to start
  - might exploit multi-hart computer
  - relies on a user provided executor

Threads vs Futures

- should not block

Using the best of both world

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- multithreaded executor :
  - use multiple thread to `poll` multiple future at the same time,
  - it is default in tokio,
- using a thread to resolve long calculation
  - the future create/acquire a thread, launch a calculation and return `pending`,
  - when the thread terminate, it wake the future and give the result
  - can also use a pool of thread

Questions ?