Concurrent programming in Rust

4SE05

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Outline

Concurrency 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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  - Good for compute-bound workloads,

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

Concurrency in Rust

Safty guarantees in Rust

The borrow checker

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- multiple immutables.

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To share object between threads and have mutability, you need to use some synchronisation primitive.

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To share object between threads and have mutability, you need to use some synchronisation primitive.

Sharing value with `Rc`

`Rc` is a smart pointer.

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

It allows for a value to have a lifetime long enough for each 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` traits

The compiler implements those traits when possible :

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The compiler implements those traits 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 thread boundaries, you might use `Arc<T>` instead of `Rc<T>`.

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

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

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

Primitives

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  - sync
    - atomics
    - mutex
    - channel
  - future
  - task

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You can build more complex primitives from basic primitives, or using unsafe blocks.

Atomics

Atomics live 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 happen before/after a store in one thread happen 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

```rust
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) -> ()
```

Interior Mutability

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

In Rust, some types allow their values to be mutated even on immutable 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 w.r.t other threads, only w.r.t its own thread.

Concurrent primitives 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.

Kinds of functions in Rust

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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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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

`Arc` must be explicitly cloned.

```
    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 writers, some are readers

Concurrent primitives for threaded concurrency

Mutex

Usecase

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A `mutex` allows to share a value between threads. Only one thread may hold a reference to the value at once. In Rust, `Mutex` is a wrapper around a non-atomic value. Each thread has a reference to the `Mutex`, but only one has a reference to the value.

Lifecycle of a Mutex

```rust
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 not be taken.

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There are two interfaces :

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

Releasing a Mutex

The mutex is released at 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, on each iteration of the loop
```

Poisoned Mutex

If a thread panics while holding a mutex, the mutex will be poisoned. A poisoned mutex cannot be taken by anyone.

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

Borrow checker

The `Mutex` allows for only one reference to the value at once.

Concurrent primitives for threaded concurrency

Channel `mpsc`

Usecase

A `Channel` allows to pass messages between contexts.

The base implementation allows multiple writers and one reader. The channel has an infinite capacity.

Creating a channel

A channel for values 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 producers.

Sending through the channel

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

Returns an error only if the `rx` is dropped. `Ok` does not mean that the message is received. This will never block.

Receiving through the channel

```rust
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>
```

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fn try_recv(&self) -> Result<T, TryRecvError>
```

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

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

Borrow checker

A channel allows to move values from one thread to an other.

Concurrent primitives for threaded concurrency

Usefull crates

ParkingLot

Another implementation of `Mutex`

- smaller
- fair

Also see the `RwLock`, for multiple immutable references or one mutable reference at the same time.

Rayon

For data parallelism, `Rayon` can be used to create thread worker

```
fn sum_of_squares(input: &[i32]) -> i32 {
    input.par_iter()
         .map(|i| i * i)
         .sum()
}
fn add_slices(a: &[f32], b: &[f32]) -> Vec<f32>{
  let iter_a = a.par_iter();
  let iter_b = b.par_iter();
  a.zip(b).map(|(a, b)| a + b).collect()
}
```

Similar to OpenMP in C. Usefull for a big number of small functions.

Async/await, `Future` and cooperative concurrence

Async/await, `Future` and cooperative concurrence

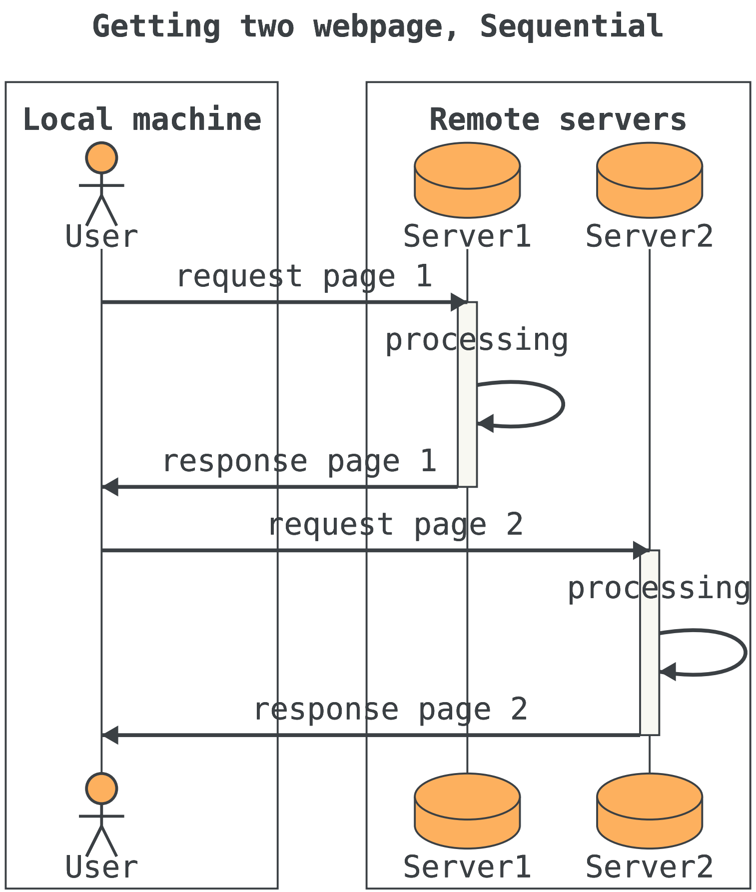
Getting two pages at the same time

Problem statement

How to get the content of two web pages ?

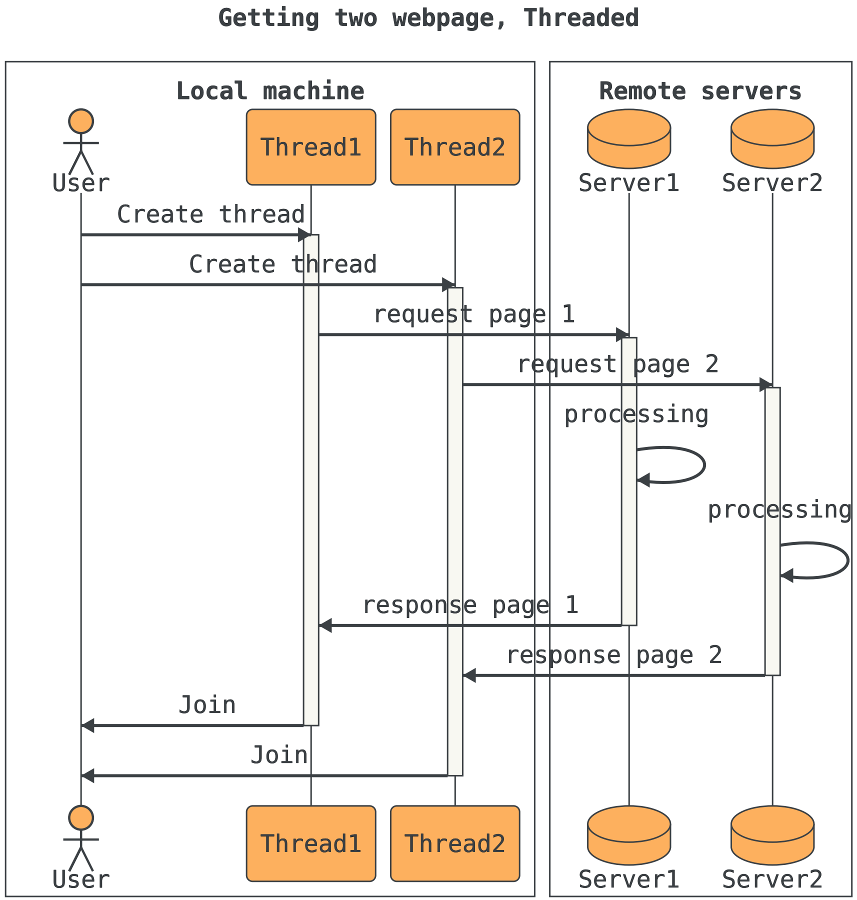
- as fast as possible
- without using too much ressources

Sequential



- simple
- slow
- use only one stack

Threaded



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

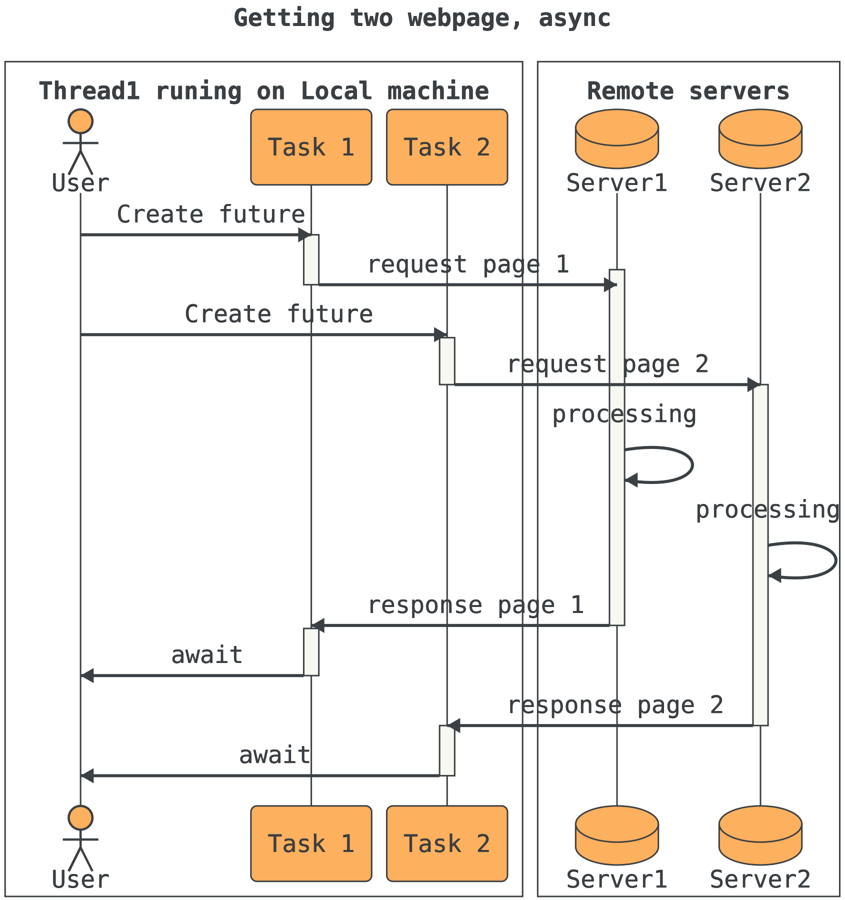
Issue with threads

- 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 task $\Longrightarrow$ one stack by task $\Longrightarrow$ heavy memory usage
  - could we use only one of 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 there is no return value)
  - can do little progress at once, stopping when they can not progress anymore or are finished
- an algorithm, the executor:
  - runs on the main thread
  - distributes compute time at each task

Async/await, `Future` and cooperative concurrence

Implementation in Rust

Futures

```rust
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 returns `Ready`.
- `Future` implementation uses a `Waker` to signal that the future is ready to be polled.
  - this allows for the 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` contains another `Future`, it should call the `poll` of the children each time it is called,
- `poll` must be quick

A delay future

```rust
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 implementing `Future` will also be generated. The `.await` marks that the future should poll the `get_slow` future.

Async and state machine

The function

```
async fn seek_value(name) -> Option<Elem> {
  let iter = name.get().await;
  for (n, elem) in iter.enumerate() {
      if check(elem).await {return elem}
  }
  None
}
```

Gives a state machine that looks like

```
enum SeekValueState{
  StateGet(name, Get),
  StateCheck(name, iter, n, elem, Check)
  }
```

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 they are awaited/polled.

Executor

The executor is the object that handle polling the tasks.

Executor

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

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

```
#[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.

Tokio, blocking tasks

To execute code that could bock, you should use `tokio::spawn_blocking`.

This will spawn a thread and await for the end of the thread.

This allows to create async interfaces from blocking interfaces.

Single thread vs multithreaded Tokio

Tokio can use multiple threads to poll multiple futures at the same time.

For futures to be shared between worker threads, they need to be `Send`.

`Send` or not

A future created with `async` is `Send` if all the variables held during an await are `Send`.

`Send` or not

A future created with `async` is `Send` if all the variables held during an await are `Send`. Holding a mutex handle during an await is not `Send`.

Good practice for async

- No blocking in async functions!

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- Do not hold a `mutex` across a `await`,

Good practice for async

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

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- multithreaded executor :
  - use multiple threads to `poll` multiple futures at the same time,
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Using the best of both worlds

- multithreaded executor :
  - use multiple threads to `poll` multiple futures at the same time,
  - it is default in tokio,
- using a thread to resolve long calculation
  - the future creates/acquires a thread, launches a calculation and returns `pending`,
  - when the thread terminates, it wakes the future and gives the result
  - can also use a pool of threads

Questions ?