Lecture 5 — Asynchronous I/O

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Geoffrey Thomas
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who called it "nonblocking async operations in Rust" and not "NO ONE SLEEP IN TOKIO"

8:39 AM · Oct 1, 2020 · Twitter Web App

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https://www.youtube.com/watch?v=Wu5TDEpAqwQ

```rust
fn main() -> io::Result<()> {
    let mut file = File::open("hello.txt")?;
    let mut s = String::new();
    file.read_to_string(&mut s)?;
    Ok(())
}
```

(The ? operator is an alternative to try! and unwrap.)

The problem is that the read call will block.

You don't get to use the CPU cycles while waiting.

Threads can be fine if you have some other code running to do work.

But maybe you would rather not use threads. Why not?

- potential race conditions;
- overhead due to per-thread stacks; or
- limitations due to maximum numbers of threads.

We're going to focus on low-level I/O from sockets in this part of the lecture, using the `mio` library from `tokio`.

(Sadly, not Neo-Tokyo. This is from *Akira*.)

Async file I/O is also possible via `tokio::fs` and the ideas will carry over.

One might often want to wrap the low-level I/O using higher-level abstractions, and the larger project `tokio.rs` is one way of doing that.

There are two ways to find out whether I/O is ready to be queried:
Polling and Interrupts.

`mio` uses polling.

The key idea is to give mio a bunch of event sources and wait for events to happen.

- create a Poll instance;
- populate it with event sources e.g. TCPListeners; and,
- wait for events in an event loop (Poll::poll()).

```
let poll = Poll::new()?;
let events = Events::with_capacity(128);
```

We're going to proactively create events; this data structure is used by Poll::poll to stash the relevant Event objects.

Populating the `Poll` instance: "registering event source".

This is a socket or file descriptor.

```
let mut listener = TcpListener::bind(address)?;
const SERVER: Token = Token(0);
poll.registry().register(&mut listener, SERVER, Interest::READABLE)?;
```

You're telling it to check for when the `listener` indicates that something is available to read.

We're ready to wait for events on any registered listener.

```rust
loop {
    poll.poll(&mut events, Some(Duration::from_millis(100)))?;

    for event in events.iter() {
        match event.token() {
            SERVER => loop {
                match listener.accept() {
                    Ok((connection, address)) => {
                        println!("Got a connection from: {}", address);
                    },
                    Err(ref err) if would_block(err) => break,
                    Err(err) => return Err(err),
                }
            }
        }
    }
}

fn would_block(err: &io::Error) -> bool {
    err.kind() == io::ErrorKind::WouldBlock
}
```

`poll.poll` will populate `events`, and waits for at most 100 ms.

If all you want to do is request a web page in Rust, use the `reqwest` library.

```rust
let body = reqwest::get("https://www.rust-lang.org")
    .await?
    .text()
    .await?;

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

(If you are doing multiple requests, you should create your own `Client` and get from it instead of `reqwest::get`).

The use of `await` is a bit tricky.

The `get` function returns a *future*.

What's that?

It's an object that will, at some point in the future, return a second object.

There are many possible definitions of `async/await`, and the appropriate one depends on your context.

Rust allows you to specify a runtime which defines the meaning of `async/await` for your program.

The simplest `await` just blocks and waits on the current thread for the result to be ready.

```rust
use futures :: executor :: block_on ;

async fn hello_world ( ) {
  println! ( "hello" ) ;
}

fn main ( ) {
  let future = hello_world ( ) ;
  block_on ( future ) ;
}
```

tokio includes a more sophisticated executor as well.

When there are multiple active awaits, tokio can multiplex them onto different threads.

You can specify the tokio executor (or others) with a tag above main() and by declaring main() to be async

```
#[tokio::main]
async fn main() {
    // do async stuff
}
```

libcurl is a C library for transferring files.

First we'll start with the easy interface.

This is a synchronous interface that uses callbacks.

```rust
use std::io::{stdout, Write};

use curl::easy::Easy;

// Write the contents of rust-lang.org to stdout
let mut easy = Easy::new();
easy.url("https://www.rust-lang.org/").unwrap();
easy.write_function(|data| {
    stdout().write_all(data).unwrap();
    Ok(data.len())
}).unwrap();
easy.perform().unwrap();
```

Note that we provide a lambda as a callback function.

This lambda is to be invoked when the library receives data from the network (i.e. write_function()).

In the body of the lambda, we simply write the received data to `stdout` and return the number of bytes we processed (all of them, in this case).

Looking at the original libcurl documentation, you'll see how the Rust bindings are a fairly straightforward translation.

We call `easy.perform()` to, well, perform the request, blocking until it finishes, and using the callback to process the received data.

The real reason we're talking about libcurl is the asynchronous multi interface.

Network communication is a great example of asynchronous I/O.

You can start a network request and move on to creating more without waiting for the results of the first one.

For requests to different recipients, it certainly makes sense to do this.

The main tool here is the "multi handle".

The structure for the new multi-handle type is `curl::multi::Multi`.
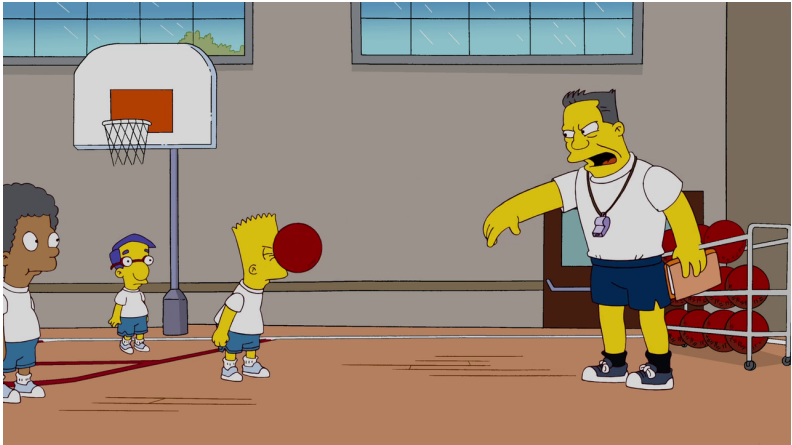
The multi functions may return a `MultiError` rather than the easy `Error`.

Once we have a multi handle, we can add easy objects—however many we need—to the multi handle.

Creation of the easy object is the same as it is when being used alone.

Then, we add the easy (or easy2) object to the multi handle with `add()` (or `add2()`).

The `add()` or `add2()` functions return an actual easy handle.

Once we have finished putting all the easy handles into the multi handle, we can dispatch them all at once with `perform()`.

This function returns, on success, the number of easy handles in that multi handle that are still running.

If it's down to 0, then we know that they are all done.

This does mean that we're going to call `perform()` more than once.

Doing so doesn't restart or interfere with anything that was already in progress.

We can check often, but the intention is to do other stuff in the meantime.

Suppose we've run out of things to do though.

We can wait, if we want, using `wait()`.

This function will block the current thread until something happens.

The first parameter to `wait()` is an array of extra file descriptors you can wait on (but we will always want this to be `&mut []` in this course).

Things are now in motion that cannot be undone.

In the meantime though, the perform operations are happening, and so are whatever callbacks we have set up (if any).

As the I/O operation moves through its life cycle, the state of the easy handle is updated appropriately.

Each easy handle has an associated status message as well as a return code.

We pass `messages()` a callback which finds out what happened and makes sure all is well.

What we are looking for is that the callback's parameter `msg` has `result_for` including Some—request completed.

If not, this request is still in progress and we aren't ready to evaluate whether it was successful or not.

If there are more handles to look at, we should go on to the next. If it is done, we should look at the result.

If it is `Error` then there is an error. Else, everything succeeded.

When a handle has finished, you need to remove it from the multi handle.

Remove the handle you got back from `add/2` with `remove/2`.

You don't have to cleanup the easy handle because Rust.

```rust
const URLS:[&str; 4] = [
  "https://www.microsoft.com",
  "https://www.yahoo.com",
  "https://www.wikipedia.org",
  "https://slashdot.org" ];

use curl::Error;
use curl::easy::{Easy2, Handler, WriteError};
use curl::multi::{Easy2Handle, Multi};
use std::time::Duration;
use std::io::{stdout, Write};

struct Collector(Vec<u8>);
impl Handler for Collector {
    fn write(&mut self, data: &[u8]) -> Result<usize, WriteError> {
        self.0.extend_from_slice(data);
        stdout().write_all(data).unwrap();
        Ok(data.len())
    }
}
fn init(multi:&Multi, url:&str) -> Result<Easy2Handle<Collector>, Error> {
    let mut easy = Easy2::new(Collector(Vec::new()));
    easy.url(url)?;
    easy.verbose(false)?;
    Ok(multi.add2(easy).unwrap())
}
```

```rust
fn main() {
    let mut easys : Vec<Easy2Handle<Collector>> = Vec::new();
    let mut multi = Multi::new();

    multi.pipelining(true, true).unwrap();
    for u in URLS.iter() {
        easys.push(init(&multi, u).unwrap());
    }
    while multi.perform().unwrap() > 0 {
        // .messages() may have info for us here...
        multi.wait(&mut [], Duration::from_secs(30)).unwrap();
    }

    for eh in easys.drain(..) {
        let mut handler_after:Easy2<Collector> = multi.remove2(eh).unwrap();
        println!("got response code {}", handler_after.response_code().unwrap
            ());
    }
}
```
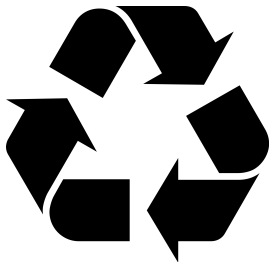
Image Credit: Wikipedia user Krdan

Can we re-use an easy handle rather than destroy and create a new one?

The official docs say that you can re-use one.

But you have to remove it from the multi handle and then re-add it.

... presumably after having changed anything that you want to change about that handle.

You could have a situation where there are constantly handles in progress.

You might never be at a situation where there are no messages left.

And that is okay.

The developer claims that you can have multiple thousands of connections in a single multi handle.
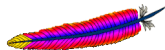
60k ought to be enough for anyone!

- Blocking I/O; 1 process per request.
- Blocking I/O; 1 thread per request.
- Asynchronous I/O, pool of threads,
  callbacks,
  each thread handles multiple connections.
- Nonblocking I/O, pool of threads,
  multiplexed with select/poll, event-driven,
  each thread handles multiple connections.

Old Apache model:

- Main thread waits for connections.
- Upon connect, forks off a new process,
  which completely handles the connection.
- Each I/O request is blocking:
  e.g. reads wait until more data arrives.

Advantage:

- "Simple to understand and easy to program."

Disadvantage:

- High overhead from starting 1000s of processes.
  (can somewhat mitigate with process pool).

Can handle $\sim$10 000 processes, but doesn't generally scale.

We know that threads are more lightweight than processes.

Same as 1 process per request, but less overhead.

I/O is the same—still blocking.

Advantage:

- Still simple to understand and easy to program.

Disadvantages:

- Overhead still piles up, although less than processes.
- New complication: race conditions on shared data.

In 2006, perf benefits of asynchronous I/O on lighttpd[1]:

version		fetches/sec	bytes/sec	CPU idle
1.4.13	sendfile	36.45	3.73e+06	16.43%
1.5.0	sendfile	40.51	4.14e+06	12.77%
1.5.0	linux-aio-sendfile	72.70	7.44e+06	46.11%

(Workload: 2×7200 RPM in RAID1, 1GB RAM,
        transferring 10GBytes on a 100MBit network).

_____

[1] http://blog.lighttpd.net/articles/2006/11/12/lighty-1-5-0-and-linux-aio/

Basic workflow:

1. enqueue a request;
2. … do something else;
3. (if needed) periodically check whether request is done; and
4. read the return value.

See the ECE 252 notes if you want to learn about select/poll!