Asynchrony Deep Dive

PoolC 양제성

Source: 2024/11/22 (Fri)

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Warm up!

Application

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Misconceptions on Promise

```
const p = new Promise((resolve, reject) => {
  setTimeout(() => resolve("done"), 1000)
})

p.then(console.log)
console.log("I'm gonna be printed first!")
```

Misconceptions on Promise

```
const p = new Promise((resolve, reject) => {
  for (let i = 0; i < 1000000000; i++) {}
  console.log("Hmm...")
  resolve("done")
});

p.then(console.log);
console.log("Hi!");
```

Misconceptions on Promise

```javascript
async function foo() {
    for (let i = 0; i < 10000000000; i++) {}
    console.log("foo")
}
async function bar() {
    await foo()
    console.log("bar")
}

bar()
console.log("Hi!")
```

Contract of Promise

Promise doesn’t make something non-blocking

“Don’t run compute-heavy codes w/ Promise, rather use inherently non-blocking APIs by the runtime”

Misconceptions on Promise

```
async function foo() {
    for (let i = 0; i < 10000000000; i++) {}
    console.log("foo");
}
async function bar() {
    let a = 3; console.log("bar")
    await foo()
    a = 5; console.log("a =", a) // Where did `a` stored?
}
bar()
console.log("Hi")
```

Mental model of async/await

“Cooperative (↔ preemptive) multi-tasking”

…in a very high-level, abstracted view

Terminology Time!

Parallel vs. Concurrent

Parallel

1. A parallel system can run multiple tasks **simultaneously**
2. Tasks **necessarily** run at the same time
3. ex. Multi-core CPU

Concurrent

1. A concurrent system can **handle** multiple tasks
2. Tasks **not necessarily** run at the same time
3. ex. Time sharing system

async/sync & block/non-block

Synchronous blocking

- disk I/O (not really after Linux 2.5.23) TODO: see man page.
- `Promise` w/o `await`

Asynchronous non-blocking

- `setTimeout`, `fetch`, `Promise`

Synchronous blocking

- polling

Async blocking?

	Blocking	Non-blocking
Synchronous	Read/write	Read/wirte (O_NONBLOCK)
Asynchronous	i/O multiplexing (select/poll)	AIO

https://developer.ibm.com/articles/l-async/

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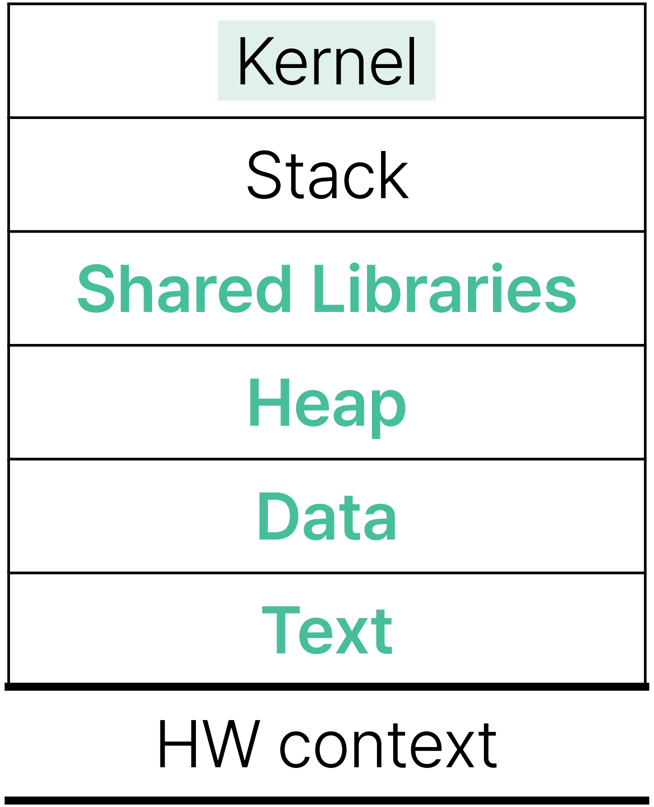
A bit of history: web servers

I/O by multi-processing

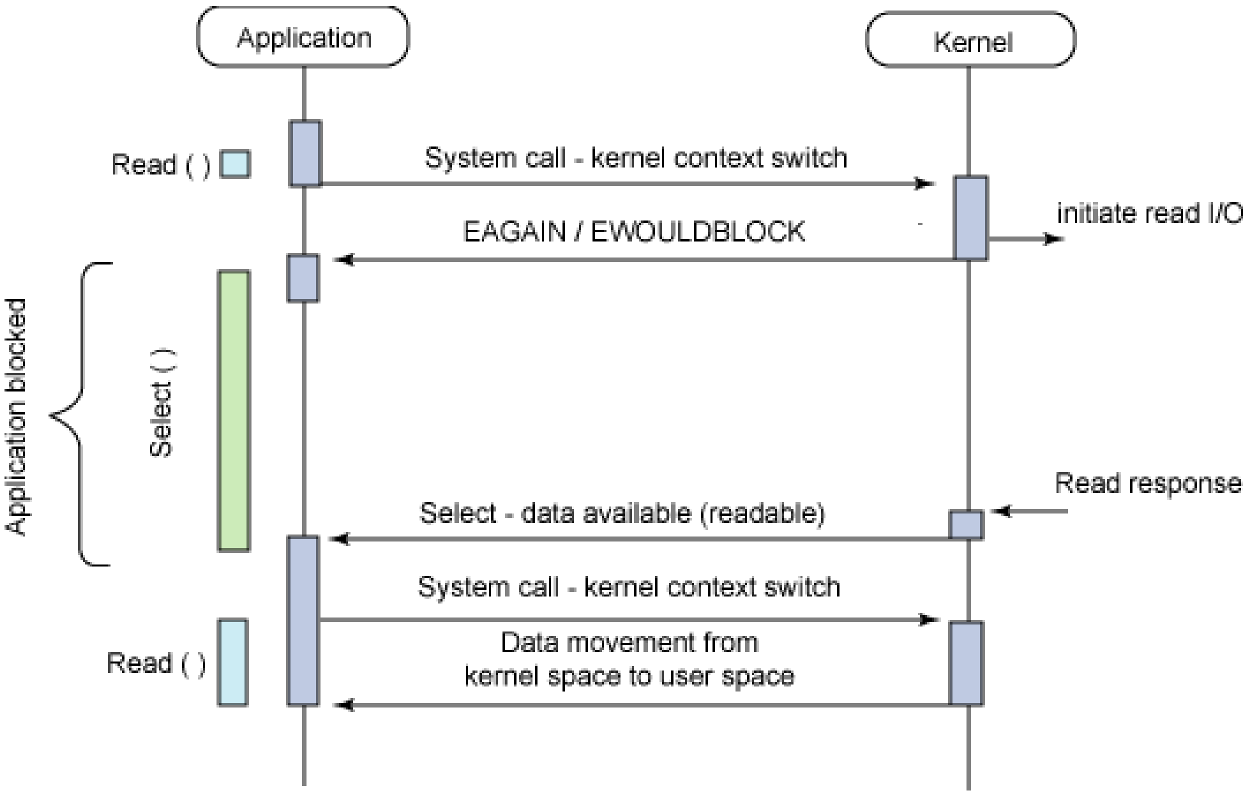
- `fork + exec`
- even w/ COW... too heavy!

I/O by multi-threading

- `pthread_create + pthread_join`
- share as much as possible



I/O multiplexing



https://developer.ibm.com/articles/l-async/

I/O multiplexing

“Do works only when it is possible to proceed”

UNIX I/O multiplexing: `select`

```
$ man 2 select
```

- allows **a** program to **monitor multiple file descriptors**, waiting until one or more of the file descriptors become “ready” for some class of I/O operation
- A file descriptor is considered ready if it is possible to perform a corresponding I/O operation
- WARNING: can **monitor at most FD_SETSIZE (1024) file descriptors**... and this limitation will not change. All modern applications should instead use poll(2) or epoll(7)...

UNIX I/O multiplexing: `select`

CAUTION: NOT 100% CORRECT!

```
fd_set reads; FD_SET(server_socket, &readfds);

while (true) {
    select(server_socket + 1, &readfds, ...) // block
    for (auto fd : readfds) {
        if (FD_ISSET(fd, &readfds)) {
            if (fd == server_socket) {
                client_socket = accept(server_soccet, ...);
                FD_SET(client_socket, &readfds);
            } else
                read(fd, buffer, ...);
        }
    }
}
```

Linux I/O multiplexing: `epoll`

`$ man 7 epoll (since Linux 2.5.45)`

- The epoll API performs a similar task to poll(2): **monitoring multiple file descriptors** to see if I/O is possible on any of them
- The epoll API can be used either as an **edge-triggered** or a **level-triggered** interface and **scales well** to large numbers of watched file descriptors

Linux I/O multiplexing: `epoll`

CAUTION: NOT 100% CORRECT!

```c
epfd = epoll_create(EPOLL_SIZE);
ep_events = (epoll_event*) malloc(sizeof(struct epoll_event) * EPOLL_SIZE);
struct epoll_event event;
epoll_ctl(epfd, EPOLL_CTL_ADD, server_socket, &event);
```

Linux I/O multiplexing: epoll

CAUTION: NOT 100% CORRECT!

```
while (true) {
    event_count = epoll_wait(epfd, ep_events, EPOLL_SIZE, ...); // block
    for (int i = 0; i < event_count; i++) {
        if (ep_events[i].data.fd == server_socket) {
            client_socket = accept(server_socket, ...);
            ...
            event.data.fd = client_socket;
            epoll_ctl(epfd, EPOLL_CTL_ADD, client_socket, &event);
        } else
            read(ep_events[i].data.fd, buffer, ...);
    }
}
```

Linux I/O multiplexing: `epoll`

Level-triggered

- `fd` is considered ready if it is possible to perform a corresponding I/O operation
- A partially read socket is also read in the next loop (same with `select`)

Edge-triggered

- `fd` is considered ready if the I/O event has occurred since the last `epoll_wait` call
- partially read socket won’t be read in the next loop

Linux I/O multiplexing: `epoll`

level-triggered vs edge-triggered

Caution!

- When using edge-triggered mode, always make sure to use non-blocking I/O (for sockets, use `O_NONBLOCK`)
- You also need to read/write until `EWOULDBLOCK` is returned
- With this contract, it gives you more efficiency ($O(1)$ multiplexing where N is the number of file descriptors)

Linux Async I/O: `aio`

`$ man 7 aio` (since Linux 2.5.23)

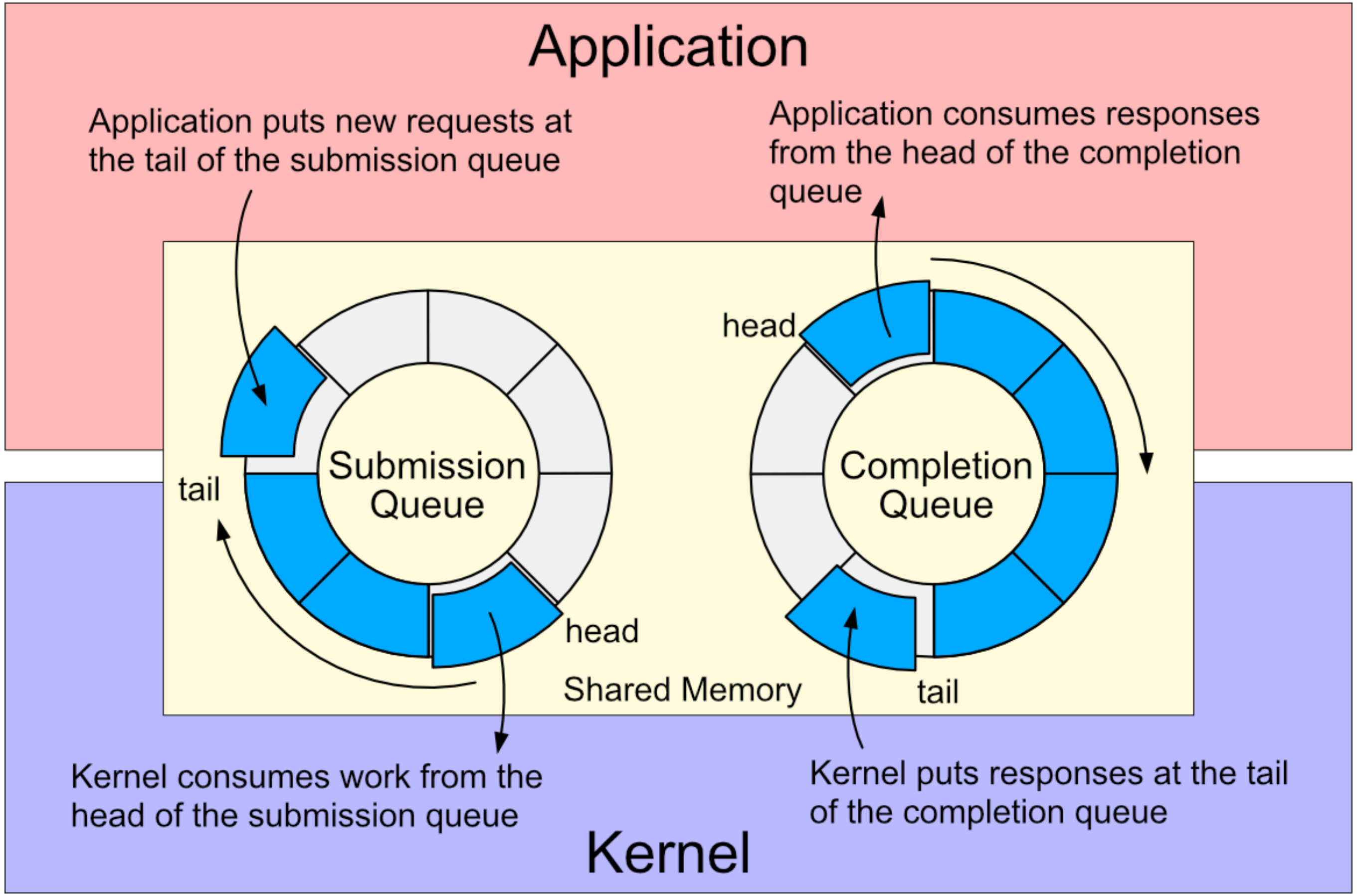
- allows applications to initiate one or more I/O operations that are performed asynchronously (i.e., **in the background**)
- The application can elect to be notified of completion of the I/O operation in a variety of ways:
  - by delivery of a signal
  - by instantiation of a thread
  - or no notification at all

Linux Async I/O: `io_uring`

`$ man 7 io_uring` `(since Linux 5.1)`

- allows the user to submit one or more I/O requests, which are processed asynchronously **without blocking the calling process**
- uses 2 buffers called "ring buffer" which are **shared between user and kernel space**; avoiding the overhead of copying data between them, where possible
- "The biggest limitation of `aio` is that it only supports async IO for `O_DIRECT` access, which bypasses cache and has size/alignment restraints" [Axboe(2019). "Efficient IO with io_uring"]

Linux Async I/O: `io_uring`



https://developers.redhat.com/articles/2023/04/12/why-you-should-use-iouring-network-io

Linux Async I/O: `liburing`

```c
struct io_uring_sqe sqe;
struct io_uring_cqe cqe;
/* get an sqe and fill in a READV operation */
sqe = io_uring_get_sqe(&ring);
io_uring_prep_readv(sqe, fd, &iovec, 1, offset);
/* tell the kernel we have an sqe ready for consumption */
io_uring_submit(&ring);
/* wait for the sqe to complete */
io_uring_wait_cqe(&ring, &cqe);
/* read and process cqe event */
app_handle_cqe(cqe);
io_uring_cqe_seen(&ring, cqe);
```

Linux Async I/O: `io_uring`

Reduced system calls

- system calls(e.g. `read`, `write`, ...) are packed(not an official term) into **a single system call**, `io_uring_enter`

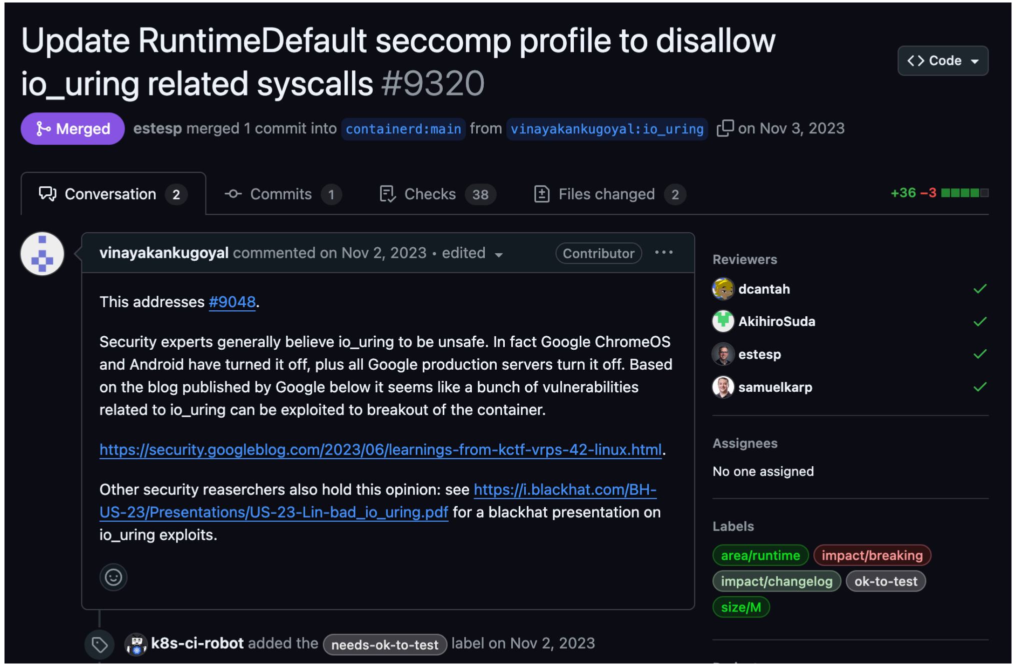
Even more reduced system calls

- supports **“Kernel side polling"**...
  - # of `io_uring_enter` calls are even reduced

- the kernel spawns a dedicated kernel thread to poll the submission queue

Linux Async I/O: `io_uring`

Sharing always causes some problems


Update RuntimeDefault seccomp profile to disallow io_uring related syscalls #9320

Code

Merged estesp merged 1 commit into `containerd:main` from `vinayakankugoyal:io_uring` on Nov 3, 2023

Conversation 2 · Commits 1 · Checks 38 · Files changed 2 · +36 −3

vinayakankugoyal commented on Nov 2, 2023 • edited · Contributor

This addresses #9048.

Security experts generally believe io_uring to be unsafe. In fact Google ChromeOS and Android have turned it off, plus all Google production servers turn it off. Based on the blog published by Google below it seems like a bunch of vulnerabilities related to io_uring can be exploited to breakout of the container.

https://security.googleblog.com/2023/06/learnings-from-kctf-vrps-42-linux.html.

Other security reasearchers also hold this opinion: see https://i.blackhat.com/BH-US-23/Presentations/US-23-Lin-bad_io_uring.pdf for a blackhat presentation on io_uring exploits.

k8s-ci-robot added the needs-ok-to-test label on Nov 2, 2023

Reviewers: dcantah, AkihiroSuda, estesp, samuelkarp

Assignees: No one assigned

Labels: area/runtime, impact/breaking, impact/changelog, ok-to-test, size/M

Limiting io_uring

To protect our users, we decided to limit the usage of io_uring in Google products:

- **ChromeOS:** We disabled io_uring (while we explore new ways to sandbox it).
- **Android:** Our seccomp-bpf filter ensures that io_uring is unreachable to apps. Future Android releases will use SELinux to limit io_uring access to a select few system processes.
- **GKE AutoPilot:** We are investigating disabling io_uring by default.
- It is disabled on production Google servers.

So… why did we go through all the way down here?
Let’s take a breath and think about the original goal…

Async runtime implementation

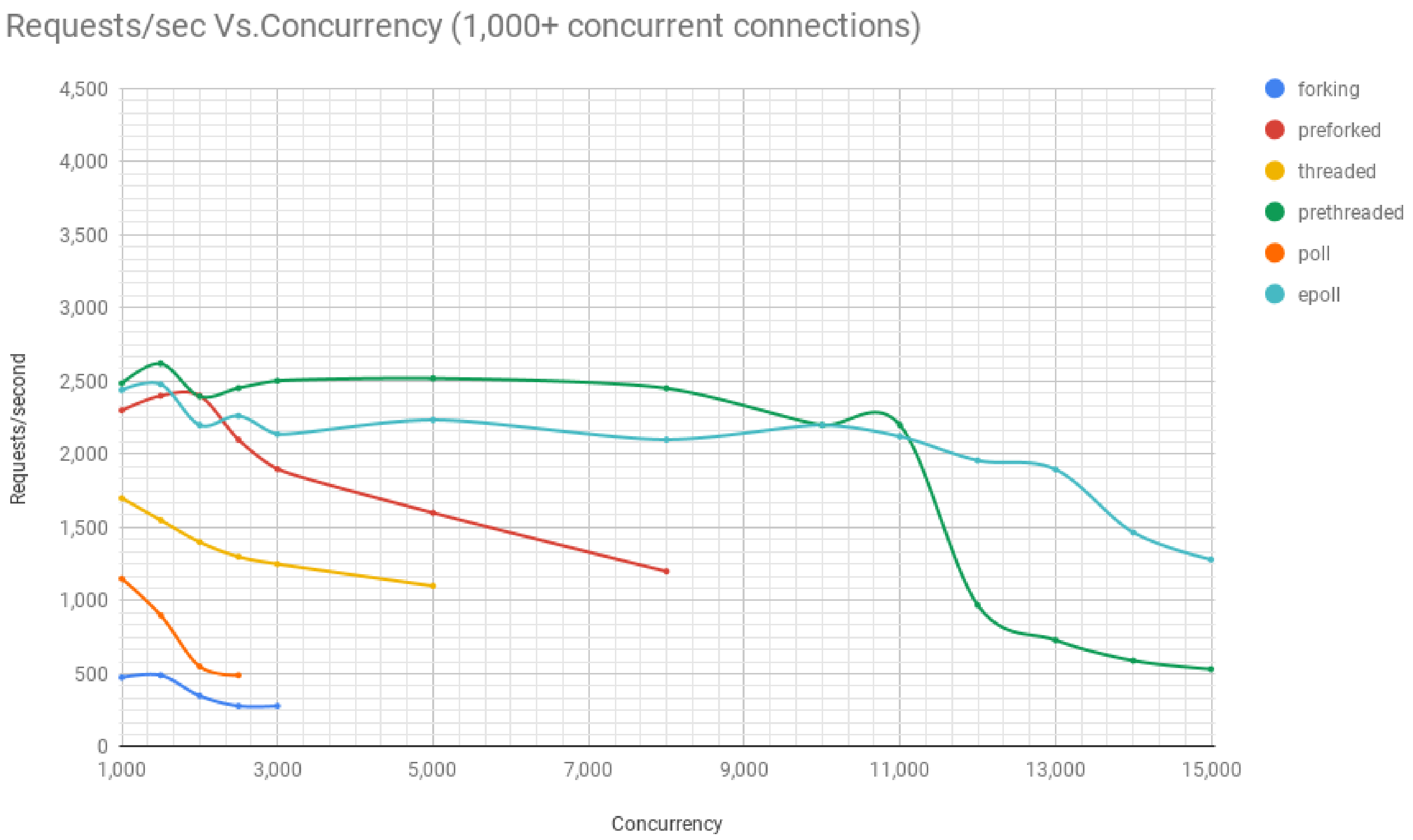
"Asynchronous systems are implemented **with the help of the kernel**!"

Async runtime implementation

Various ways to implement async runtime

- forking
- pre-forked
- threaded
- pre-threaded (a.k.a. thread pool)
- I/O multiplexing

Async runtime implementation



https://unixism.net/loti/async_intro.html

Async runtime implementation

1. “As you can see, prethreaded, or **the thread pool based web server gives the epoll(7) based server a run for its money up until a concurrency of 11,000 users** in this particular benchmark.
2. And that is a lot of concurrent users. ...
3. This is very significant, given that in terms of complexity, **thread pool based programs are way easier to code** compared to their asynchronous counterparts.
4. This also means **they are way easier to maintain** as well, since they are natually a lot easier to understand."

Async runtime implementation

Node.js

- use a **cross-platform library** `libuv` as its event loop
- `libuv` uses OS-specific I/O multiplexing system calls to handle multiple I/O operations
  - Linux: `epoll`, `io_uring` (since Node.js 20.3.0)
  - BSD: `kqueue`
  - Windows: `IOCP`
- `libuv` also maintains a thread pool(!) for DNS operations and **file system operations**

Async runtime implementation

Let’s dig in and see how `libuv` gives us the asynchronous capability!

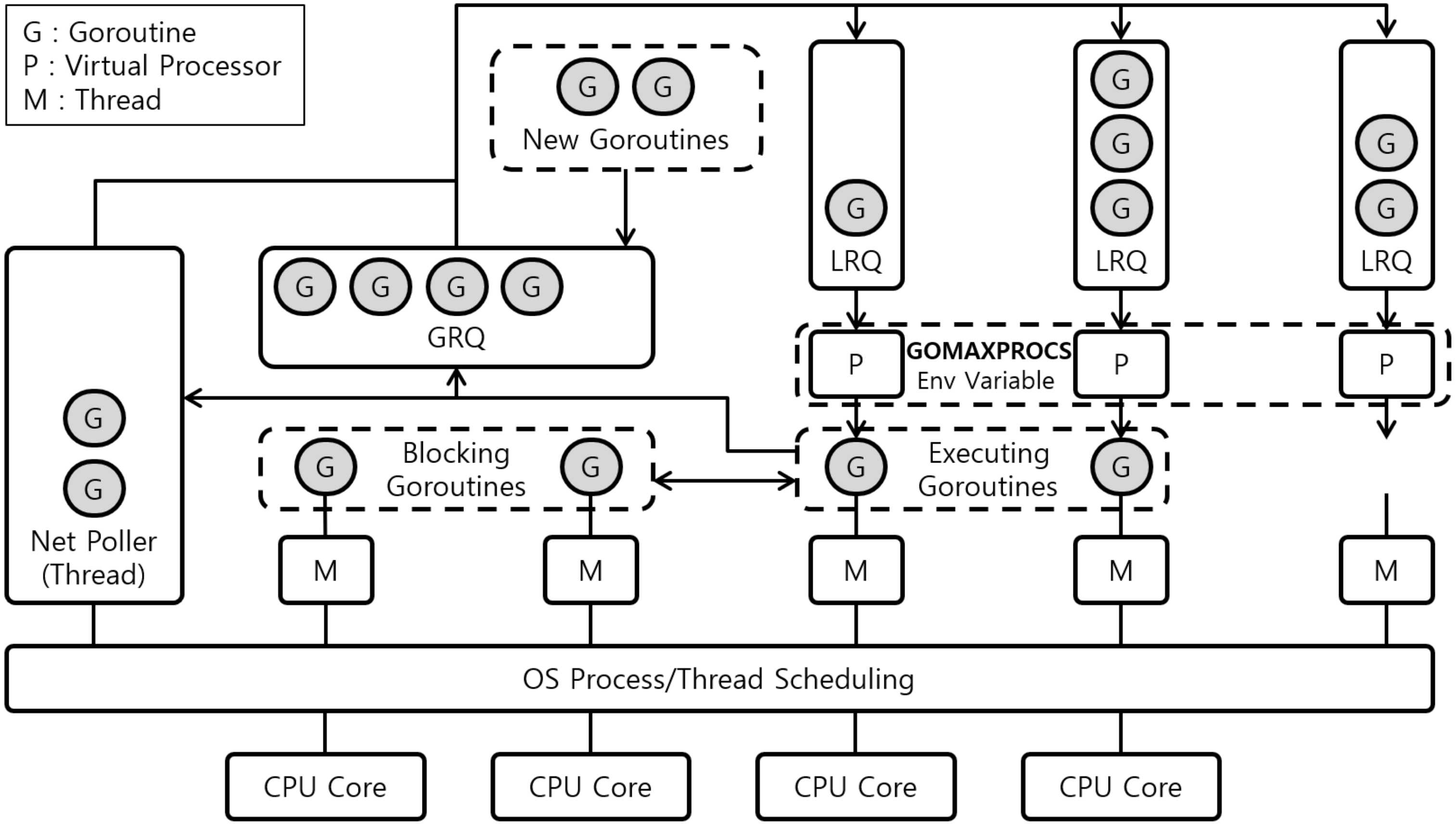
https://github.com/J3m3/node-experiment/

Async runtime implementation

Golang

- use **green thread** model to provide async capability
- **M:N threading model** (M user threads → N kernel threads)
- goroutines, **stackful coroutines**!
- delegates inherently blocking system calls to different OS threads
- **net poller** thread for I/O multiplexing

Async runtime implementation



https://velog.io/@khsb2012/go-goroutine

Async runtime implementation

Rust

- green thread(!) model (until Rust 0.9)
- **stackless couroutine** apporach
- `Future` trait (something like `Promise` but **inert**)
- Rust **standard library does not provide async runtime**;
  they are provided by external crates like `tokio`, `async-std`, etc.

Async runtime implementation

Rust (tokio crate)

- one of the **executor** of `Future` (again, `Future` is inert)
- uses `mio` crate for **I/O multiplexing**
- multiple executor instances can run in **parallel**
- **Async mutexes**?

“The spawned task may be executed on the same thread as where it was spawned, or it may execute on a different runtime thread. The task can also be moved between threads after being spawned.”

Async runtime implementation

```rust
// Let's assume we use a single-threaded runtime
async fn main() {
    let x = Arc::new(Mutex::new(0));

    let x1 = Arc::clone(&x);
    tokio::spawn(async move {
        let mut x = x1.lock(); // mutex locked
        some_async_fn().await; // yield
    });

    let x2 = Arc::clone(&x);
    tokio::spawn(async move {
        let mut x = x2.lock(); // deadlock!
    });
}
```

Async runtime implementation


```rust
// Let's assume we use a single-threaded runtime
async fn main() {
    let x = Arc::new(Mutex::new(0));

    let x1 = Arc::clone(&x);
    tokio::spawn(async move {
        *x1.lock() += 1;
    });

    let x2 = Arc::clone(&x);
    tokio::spawn(async move {
        *x2.lock() -= 1; // What about now?
    });
}
```

Choosing the right I/O strategy

CPU-bound tasks

- thread pool is sutiable
- what about single-threaded I/O multiplexing (e.g. Node.js)?

I/O-bound tasks

- single-threaded I/O multiplexing is suitable
- what about thread pools?

Actually, we can mix and match different strategies!

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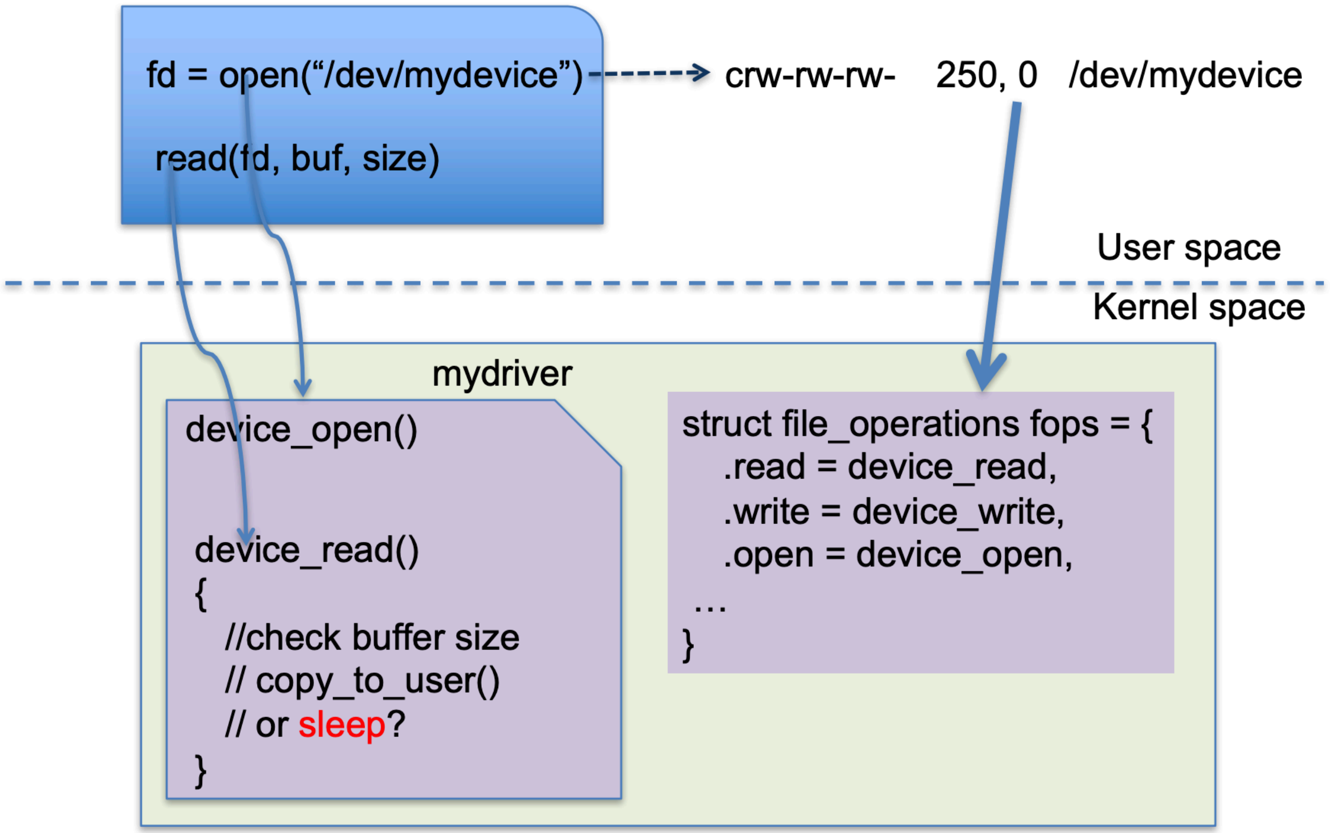
Hardware

Interrupts

How do we communicate with hardwares?

- interrupts!
- interrupt handlers, a part of a device driver, are executed when CPU receives an interrupt signal
- let's briefly see how interrupts are combined with I/O multiplexing implementation

Device driver side



Linux Device Driver by Prof. Yan Luo

`poll` syscall implementation

Some of kernel functions involved in `poll` syscall

- `sys_poll` syscall handler
- `do_poll` kernel function
- `do_pollfd` kernel function
- `xxx_poll` function defined in xxx device driver
- `poll_wait` function called by `xxx_poll`
- xxx device driver's `wake_up` function in ISR

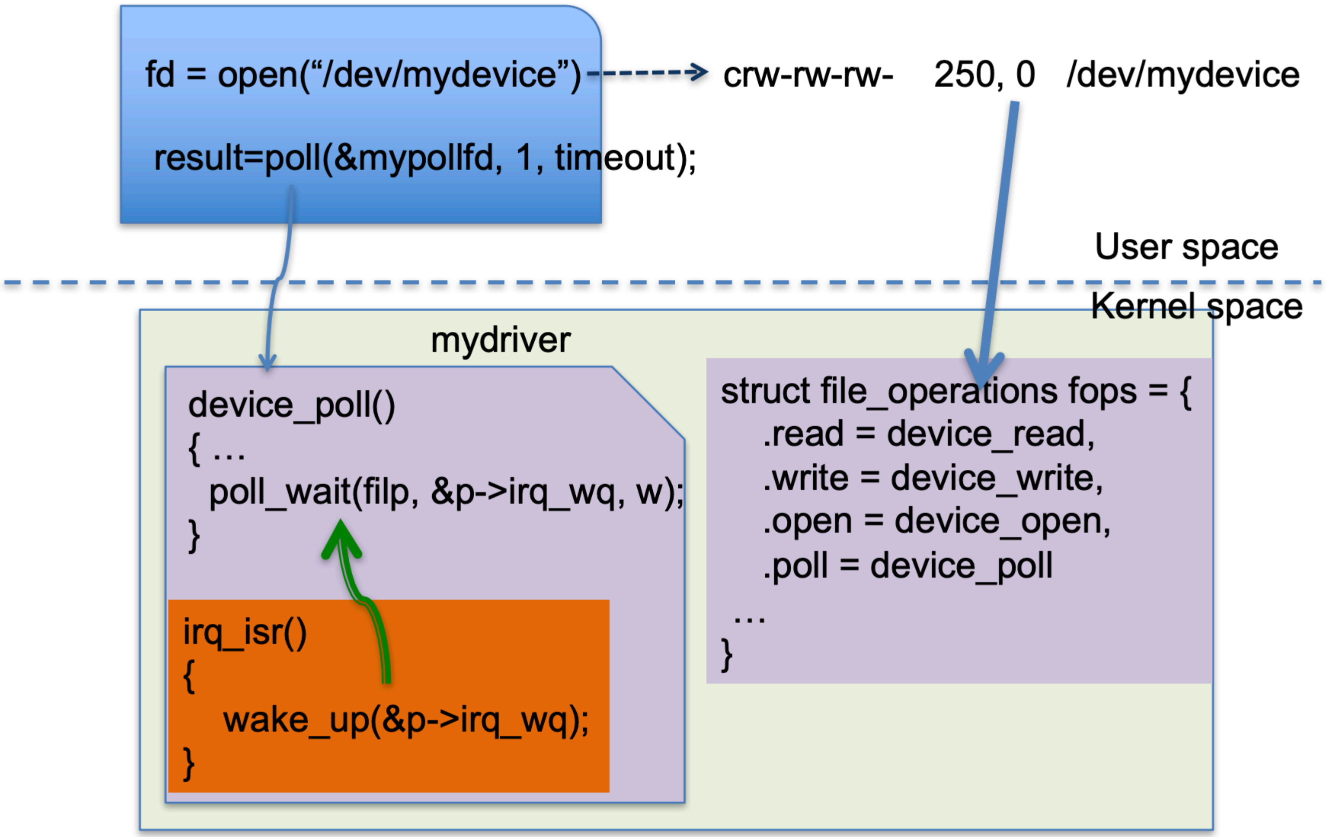
poll syscall implementation

```
foreach fd (given from user space):
  find device corresponding to fd
  call device poll function to setup wait queues \
  (with poll_wait) and to collect its "ready-now" mask

while time remaining in timeout and no devices are ready:
  sleep

return from system call (either due to timeout or to ready
devices)
```

poll in device driver



Linux Device Driver by Prof. Yan Luo

poll in device driver

```c
static __poll_t uio_poll(struct file *filep, poll_table *wait)
{
	struct uio_listener *listener = filep->private_data;
	struct uio_device *idev = listener->dev;
	__poll_t ret = 0;

	mutex_lock(&idev->info_lock);
	if (!idev->info || !idev->info->irq)
		ret = -EIO;
	mutex_unlock(&idev->info_lock);

	if (ret)
		return ret;

	poll_wait(filep, &idev->wait, wait);
	if (listener->event_count != atomic_read(&idev->event))
		return EPOLLIN | EPOLLRDNORM;
	return 0;
}
```

https://elixir.bootlin.com/linux/v6.12.1/source/drivers/uio/uio.c