Brave New Asynchronous World

Towards Asynchronous System Calls For Concurrency Platforms

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Motivation

```
void server() {
  fd = accept();

  read(fd, input);

  output = process(input);

  write(fd, output);

  close(fd);
}
```

Sequential server using blocking operations

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Sequential server using blocking operations

What if we want to serve many clients?

Motivation

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void server() {
  fd = accept();

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  write(fd, output);

  close(fd);
}
```

Sequential server using blocking operations

```
eventLoop loop;
void on_accept(fd) {
    loop.register(fd, READ);
}
void on_read(fd, input) {
    output = process(input);
    loop.register(fd, WRITE, output);
}
void on_write(fd, output) { close(fd); }
void server() {
    loop.register(listener, ACCEPT);
    loop.run();
}
```

Event-driven server

Motivation

- ☺ Handles multiple clients with just one CPU core
- ☹ Scattered logic and control flow

  von Behren et al., HOTOS'03
- How to run parallel on many cores? Threadpool?
- ☹ What if `process()` blocks?

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eventLoop loop;
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Can’t we have everything?

- Comprehensible source code
- Non-blocking IO operations
- Scalability for future many-core architectures

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Yes, we can!

Pseudo-blocking System Calls for Concurrency Platforms

Outline

1. Motivation
2. Concurrency Platforms
3. Blocking Anomaly
4. Short History of Operating-System Request Techniques
5. Concurrency Platforms and Asynchronous System Calls
6. Conclusion

Concurrency Platform

```
cilk_for (int i = 0; i < 10; ++i)
    f(i);
```

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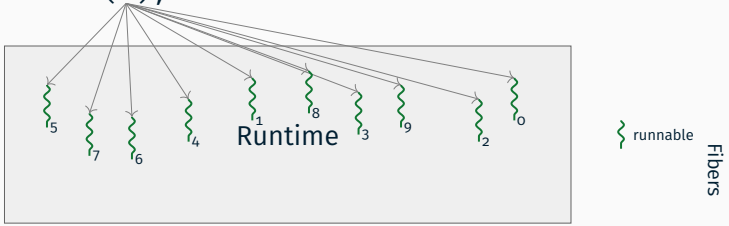

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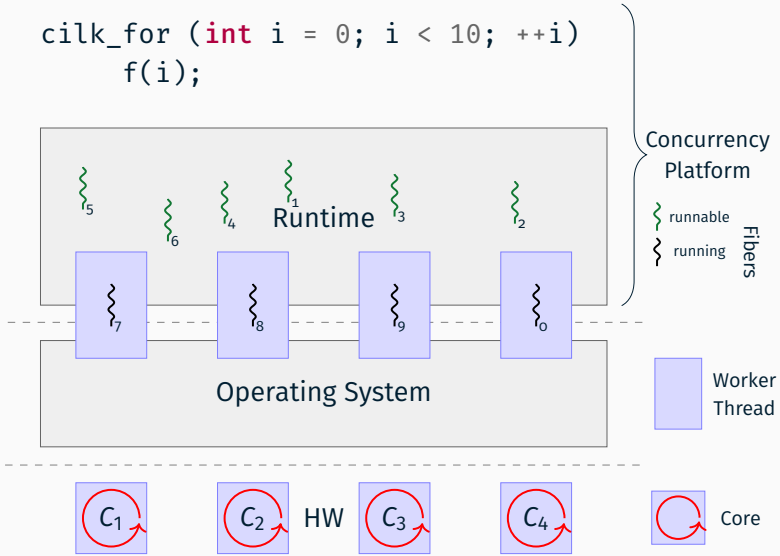

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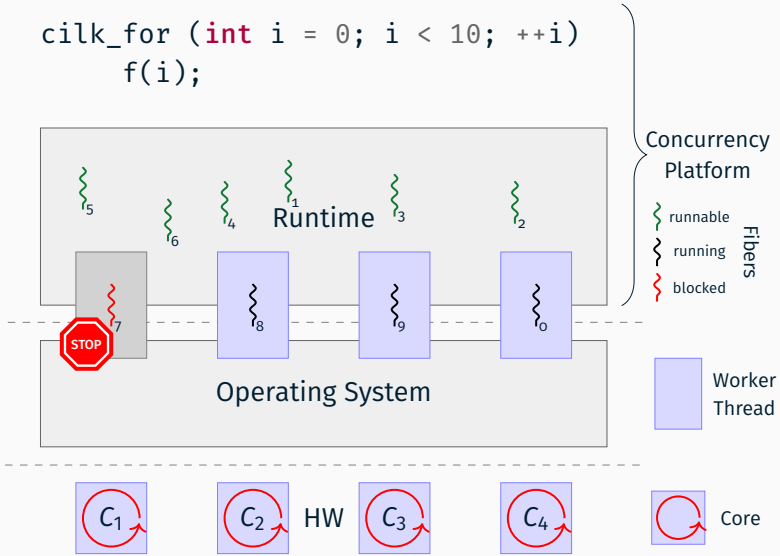

Concurrency And Blocking Syscalls

Blocking Anomaly[1]

- Blocking Fiber also blocks Worker
- $\Rightarrow$ Resources may be underutilized
- Blocking is transparent for the runtime system
- $\Rightarrow$ Requires cooperation with Operating System
- Not specific to Concurrency Platforms, also an issue with thread pools etc.

[1] Yangmin Seo et al. 1999. Supporting preemptive multithreading in the ARX real-time operating system. In *Proceedings of the IEEE Region 10 Conference*. TENCON 99. Volume 1. (September 1999), 443–446.

Approaches

- Detection (Linux Delay Accounting)

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Approaches

- Detection (Linux Delay Accounting)
- Mitigation (Scheduler Activations[2])
- Avoidance (Non-Blocking or Asynchronous System Calls)

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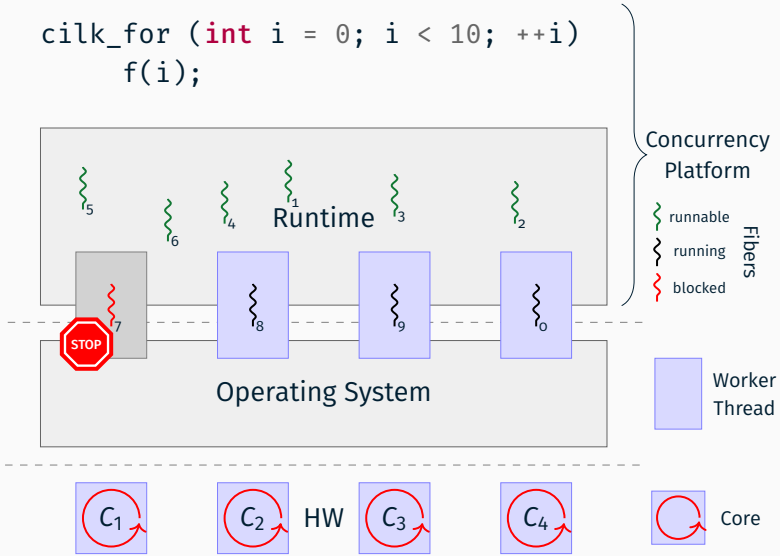
Concurrency Platform



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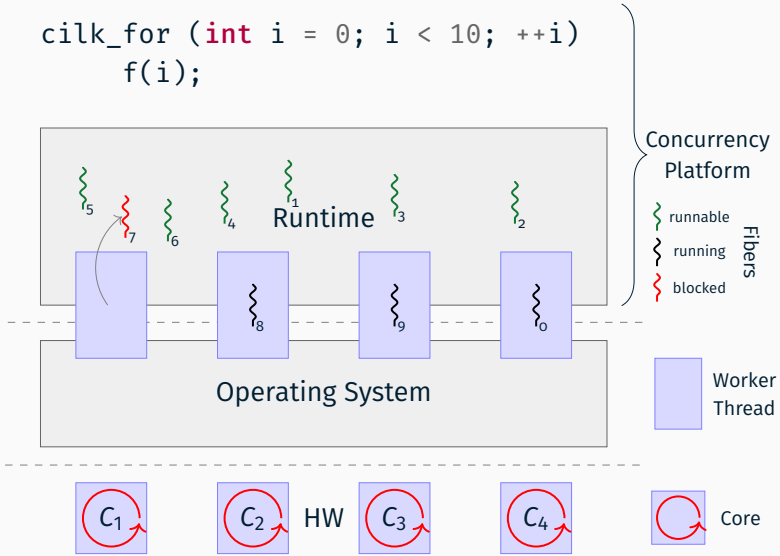

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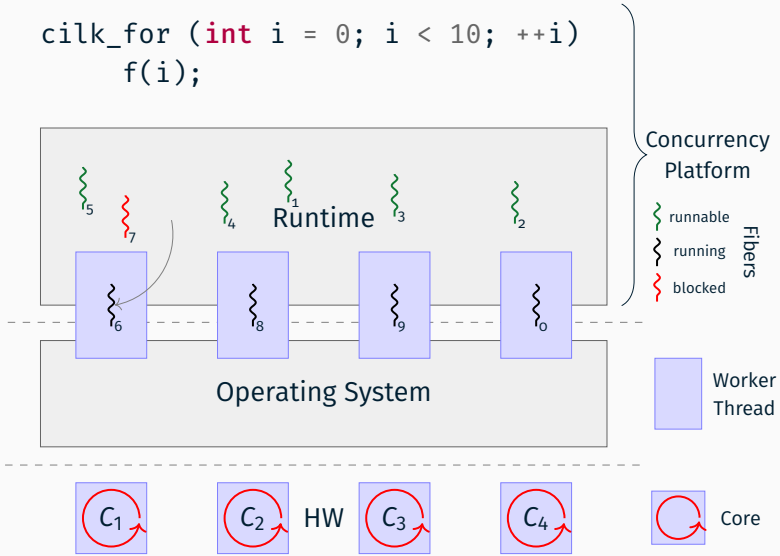

Pseudo-synchronous interface

```
ssize_t read(int fd, void* buf, size_t len) {
  ReadFuture future(fd, buf, len);
  return future.get(); // Fiber may block here.
}
```

- Transform asynchronous APIs to synchronous ones
- Base future on concurrency-platform native synchronization primitive

From here on:
IO system calls as representative of arbitrary blocking system calls.

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IO system calls as representative of arbitrary blocking system calls.

But who does fullfil the future's promise?

System (Call) Request Techniques

Kind	Technique	Examples	$\#\frac{\text{traps}}{\text{sys requests}}$
Synchronous	Blocking	e.g. `read()`/`write()`	1
Synchronous	Non-Blocking	SOCK_NONBLOCK w select/epoll	≥ 1
Asynchronous	Callback	Linux/POSIX AIO	1

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- “Traditional” Syscall Technique
- Causes Blocking Anomaly

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- C10k Problem (Kegel 1999)
- Reactor / Proactor design pattern
- ☹ Hard to implement, maintain and debug

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- Invoke callback (signal, new thread) upon system call completion
- ☹ Signal delivery impacts Instruction Per Cycle (IPC)
- ☹ New thread has a high ramp-up latency and competes with existing threads
- "AIO is a horrible ad-hoc design, ..." (Torvalds, `https://lwn.net/Articles/671657/`)

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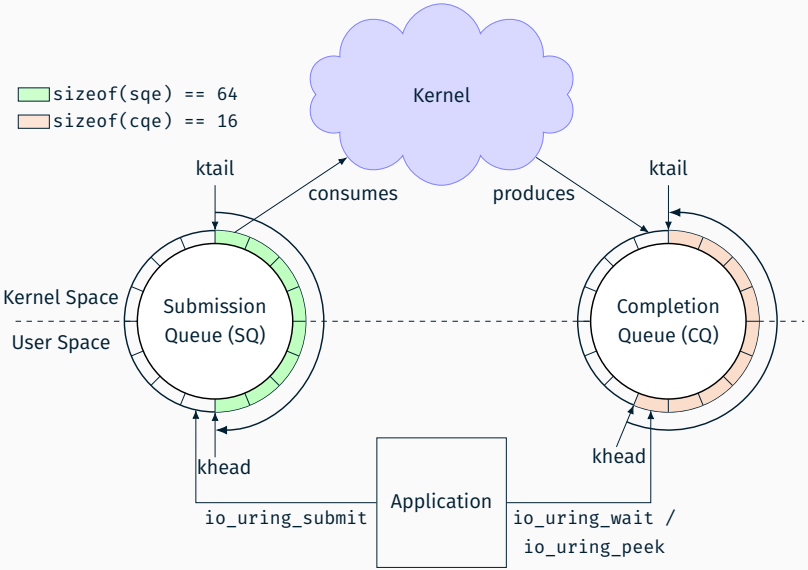
Asynchronous	Queue-based	`io_uring`	$[0, 1]$

- Soares et al. “FlexSC: Flexible System Call Scheduling with Exception-Less System Calls” (OSDI’10)
- `io_uring` introduced in Linux 5.1 (2019)
- Candidate to become **the** generic asynchronous system-call interface

io_uring Architecture



How can Concurrency Platforms exploit this asynchronous system call interface?

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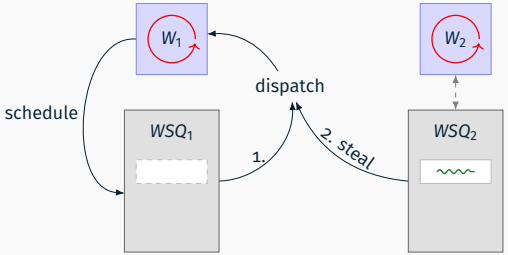
Presenting a case study based on our research Concurrency Platform **“EMPER”**

First Architecture of pseudo-synchronous System Calls



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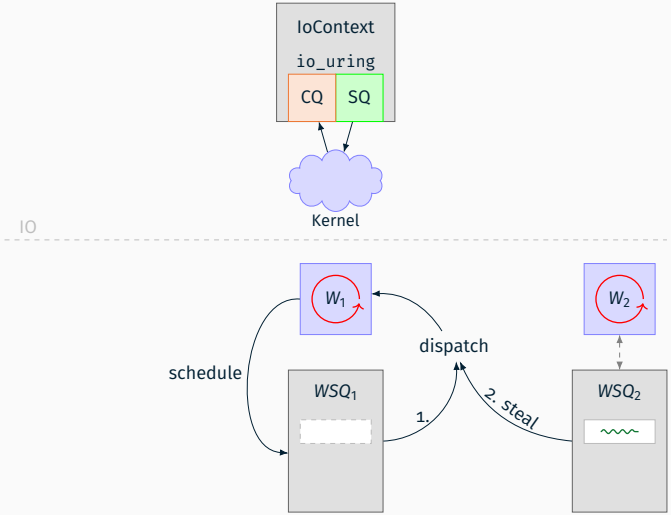

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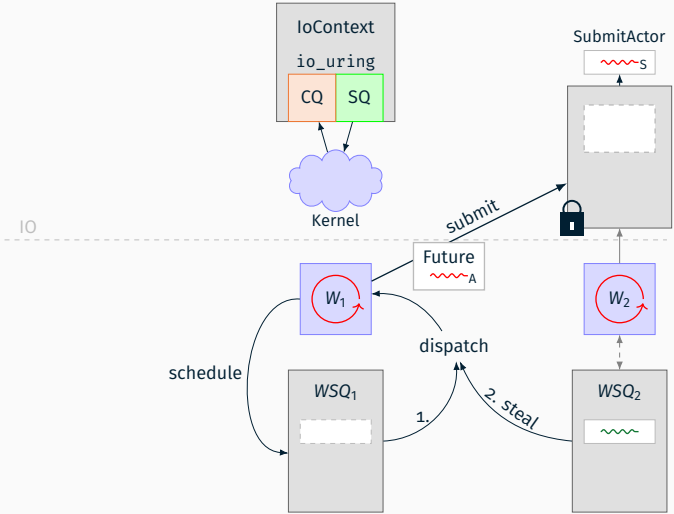

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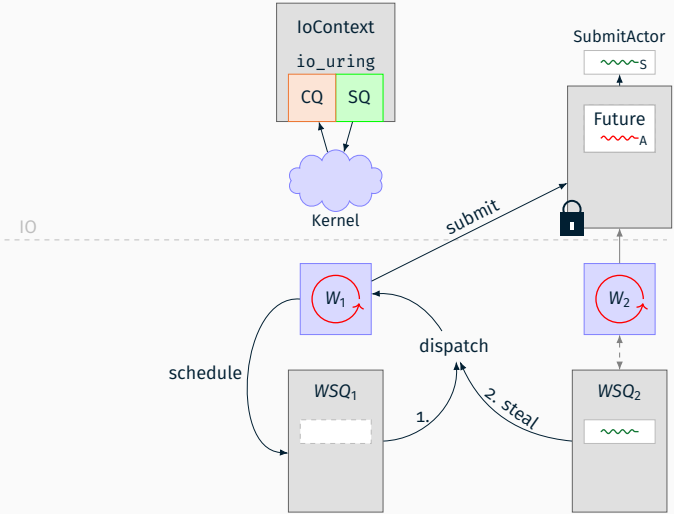

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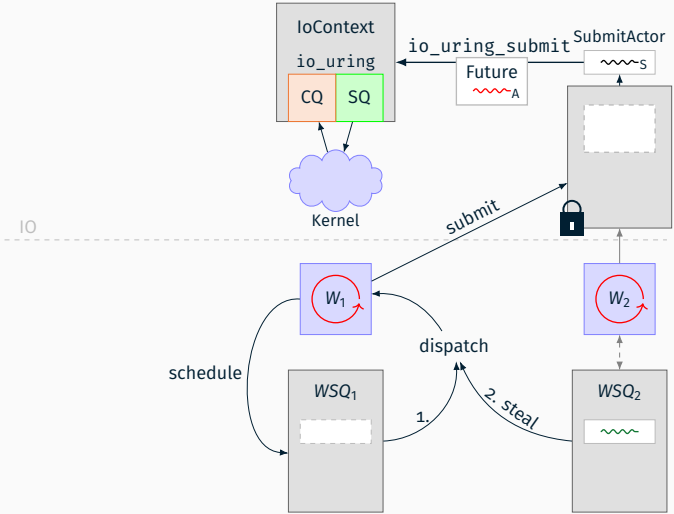

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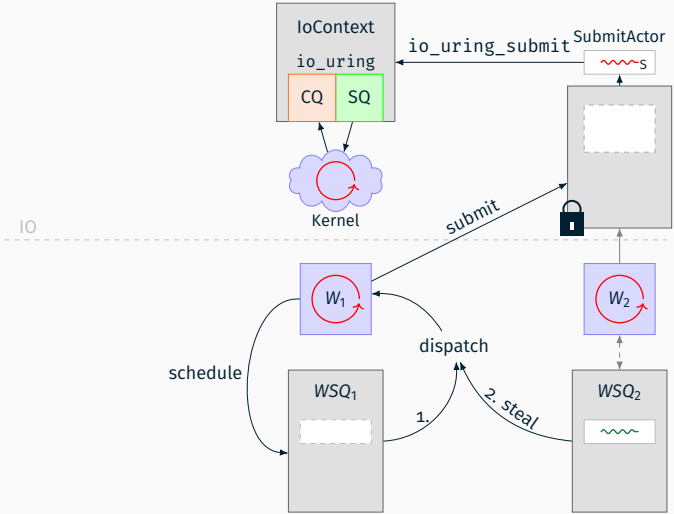

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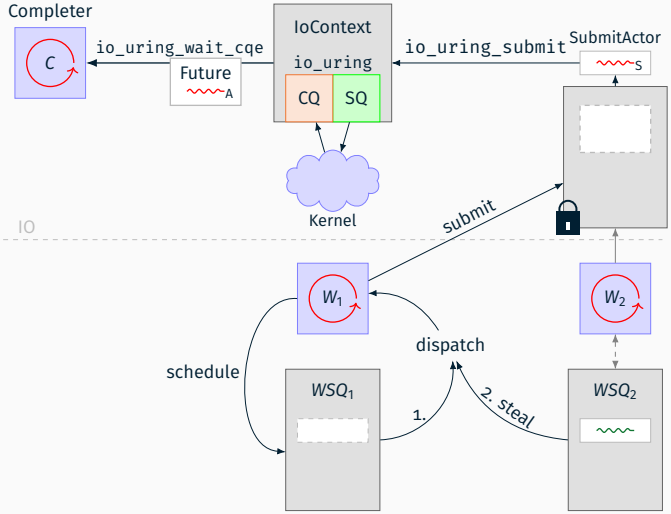

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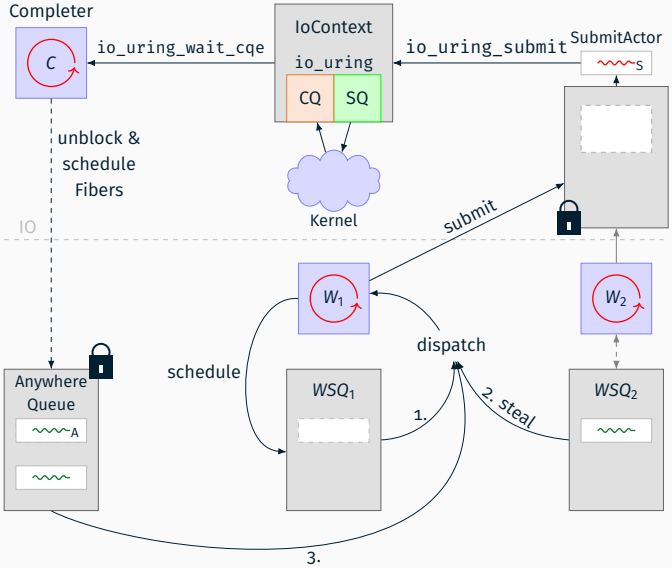

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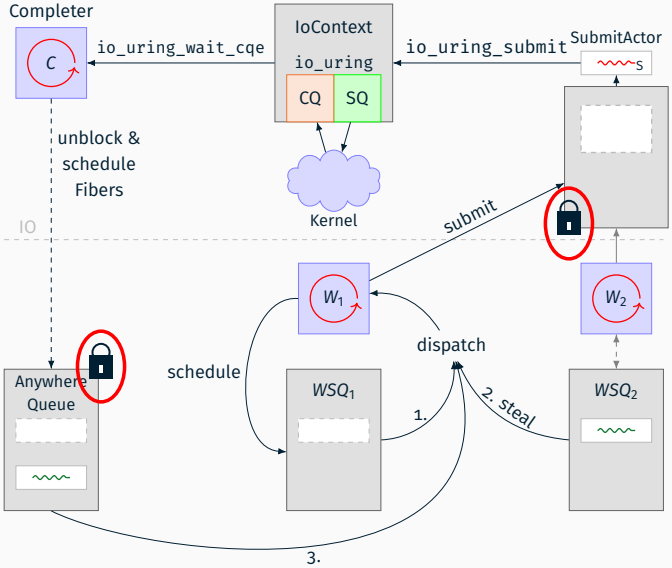

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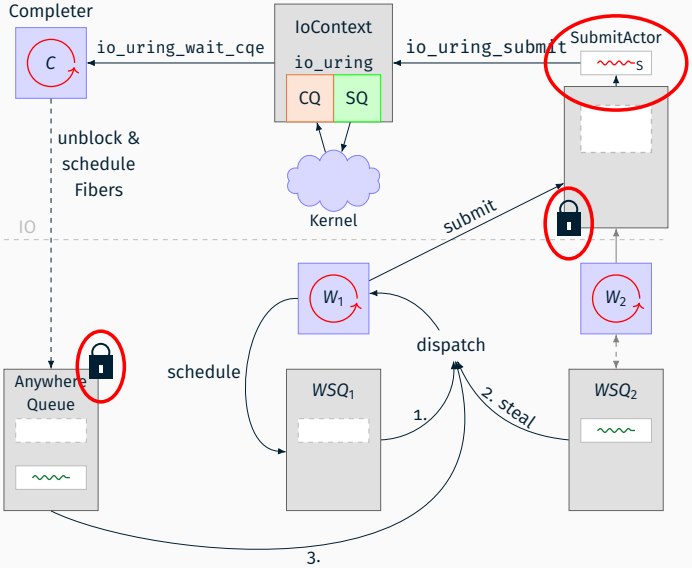
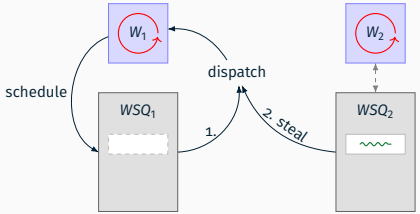


Final Architecture



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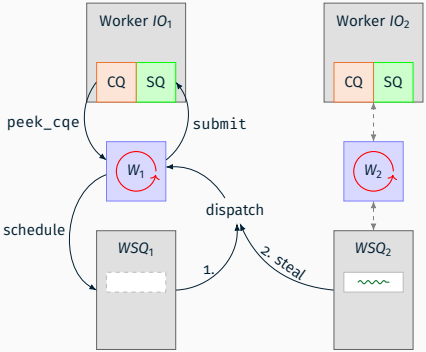

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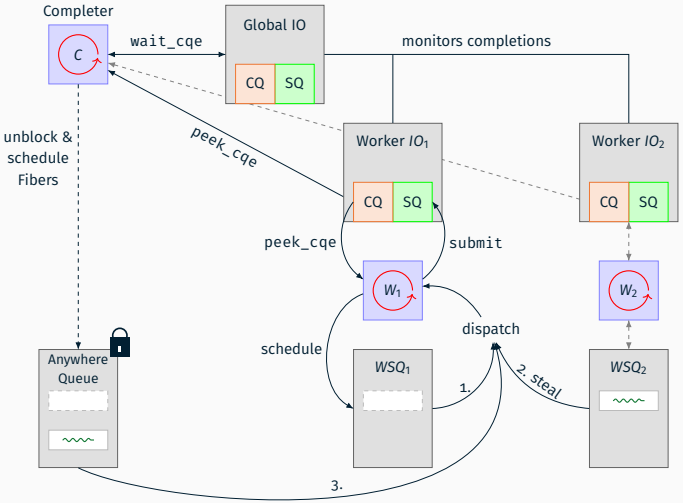

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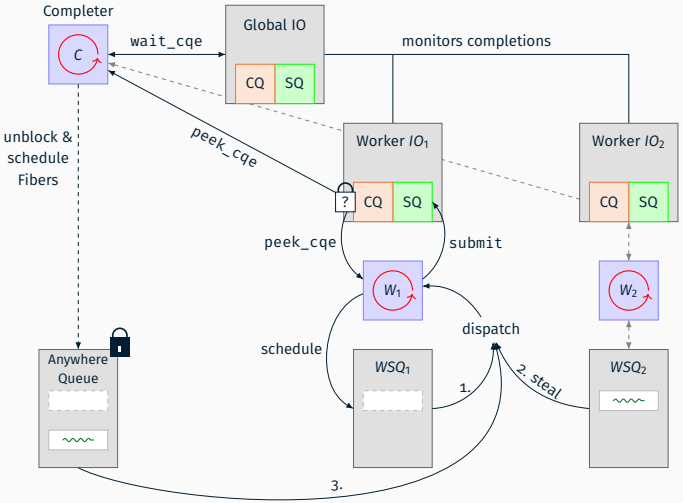

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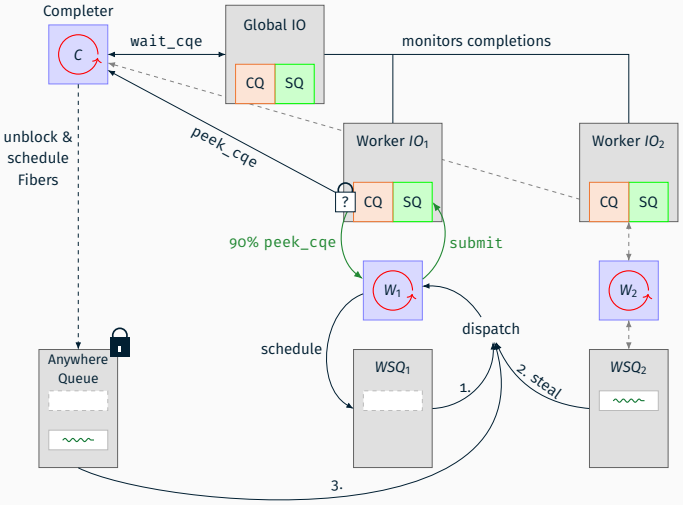

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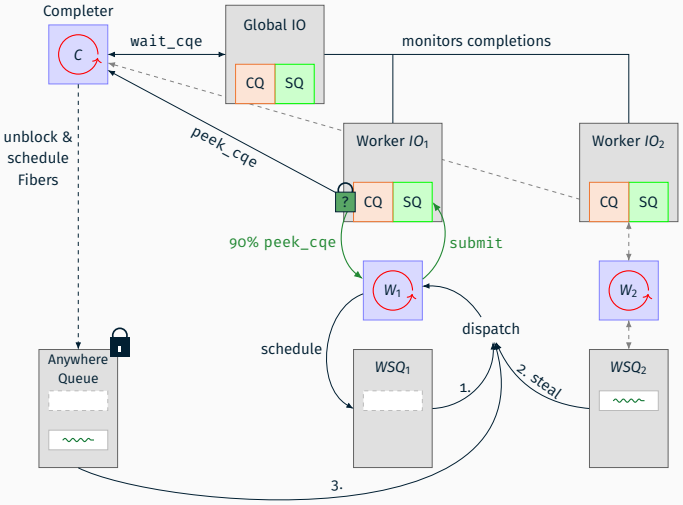
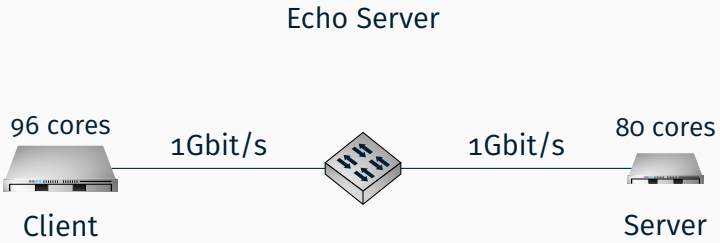


Evaluation



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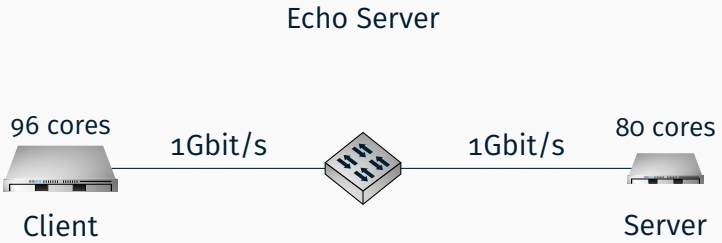
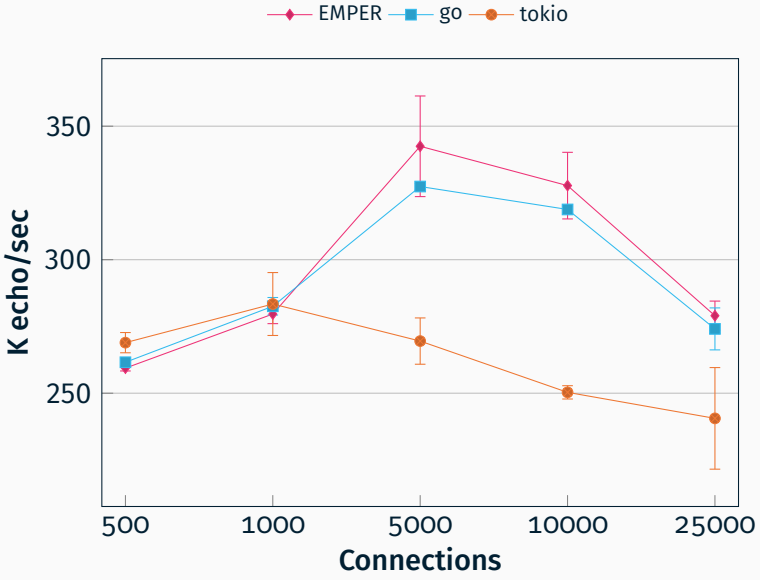
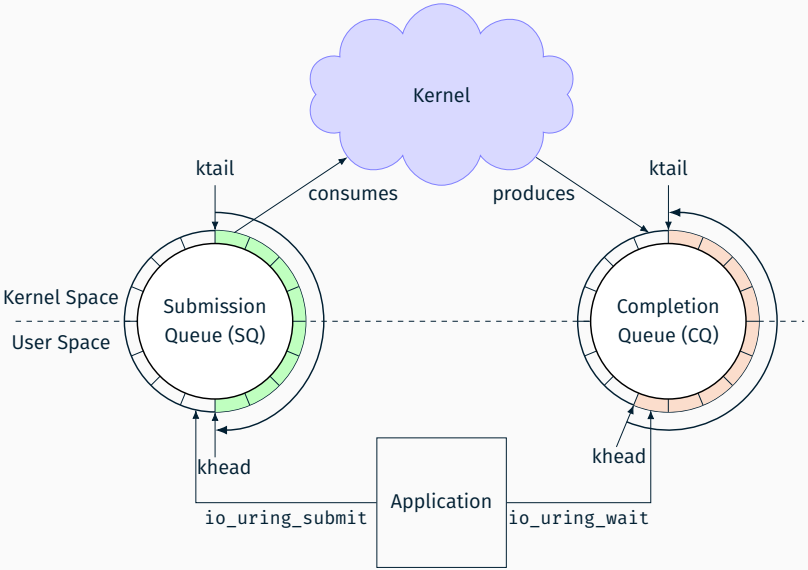


- 500 – 25.000 connections
- Linux 5.11-rc6


EMPER
go
tokio
K echo/sec
350
300
250
500
1000
5000
10000
25000
Connections

But what actually happens in the kernel?



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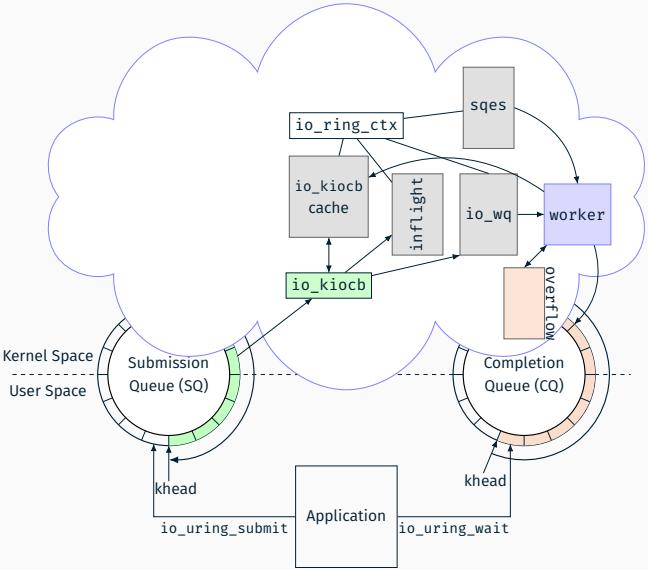

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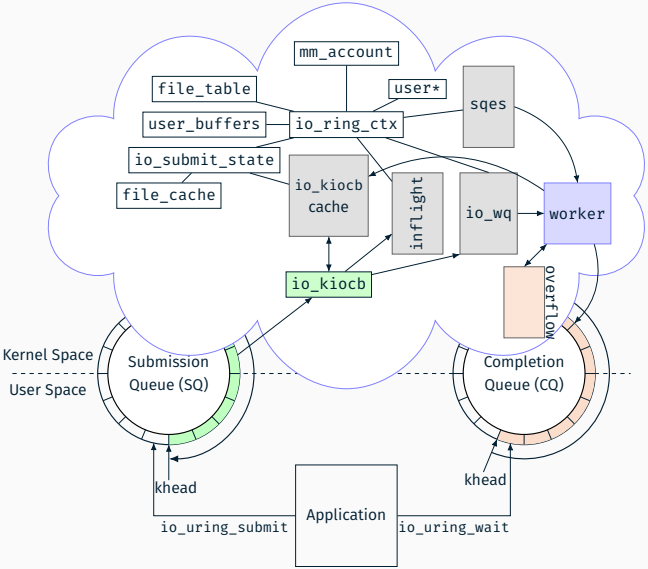

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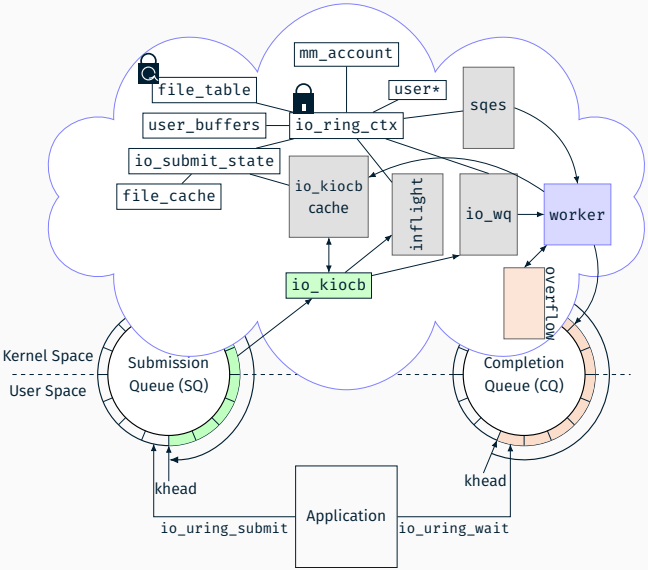

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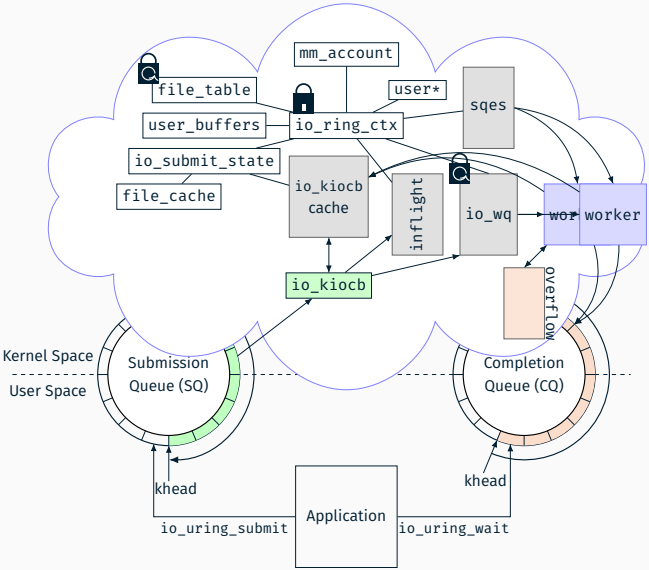

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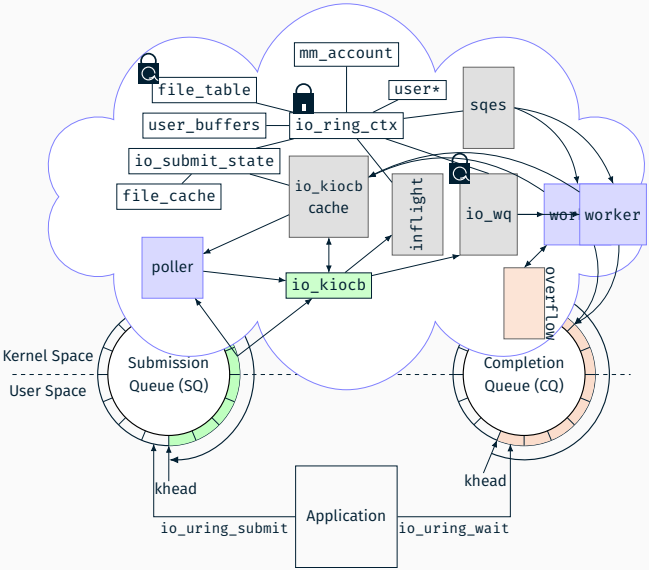

Future work

Are we building a concurrency platform in the kernel?
If yes, why not entangle both sides?

Benefits of a Concurrency Platform aware kernel

- Architectural awareness (e.g. NUMA)
- Kernel knows best how to fully use available hardware resources
- Block user-space Fibers on any trap (e.g. major page fault)

Conclusion

Fruitfully fusion of Concurrency Platforms and queue-based asynchronous system-call interfaces

- Reduce off-CPU time of application
- Again, locality is key to efficiency
- One ring (interface) to rule them all
- Many more `io_uring` techniques to exploit: `SQPOLL`, automatic buffer selection, link SQEs, ...
- Return of the M:N threading model
- Asynchronous system-call techniques are a great opportunity for operating-system research

Free Software

- https://gitlab.cs.fau.de/i4/manycore/emper
- https://gitlab.cs.fau.de/i4/manycore/emper-io-eval
- https://github.com/axboe/liburing

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Thank you for your attention!

EMPER Echoserver

```
auto main(int argc, char* argv[]) -> int {
  Runtime runtime;
  auto* listener = emper::io::tcp_listener(host, port, [](int socket) {
    char buf[1024];
    for (;;) {
      ssize_t bytes_recv = emper::io::recvAndWait(socket, buf,
                                                  sizeof(buf), 0);
      if (bytes_recv <= 0) {
      finish:
        emper::io::closeAndForget(socket); return;
      }

      ssize_t bytes_send = emper::io::sendAndWait(socket, buf,
        bytes_recv, MSG_NOSIGNAL, true);
      if (bytes_recv != bytes_send) { goto finish; }
    }
  });
  runtime.scheduleFromAnywhere(*listener);
  runtime.waitUntilFinished();
}
```