COPS: A coroutine-based priority scheduling framework perceived by the operating system

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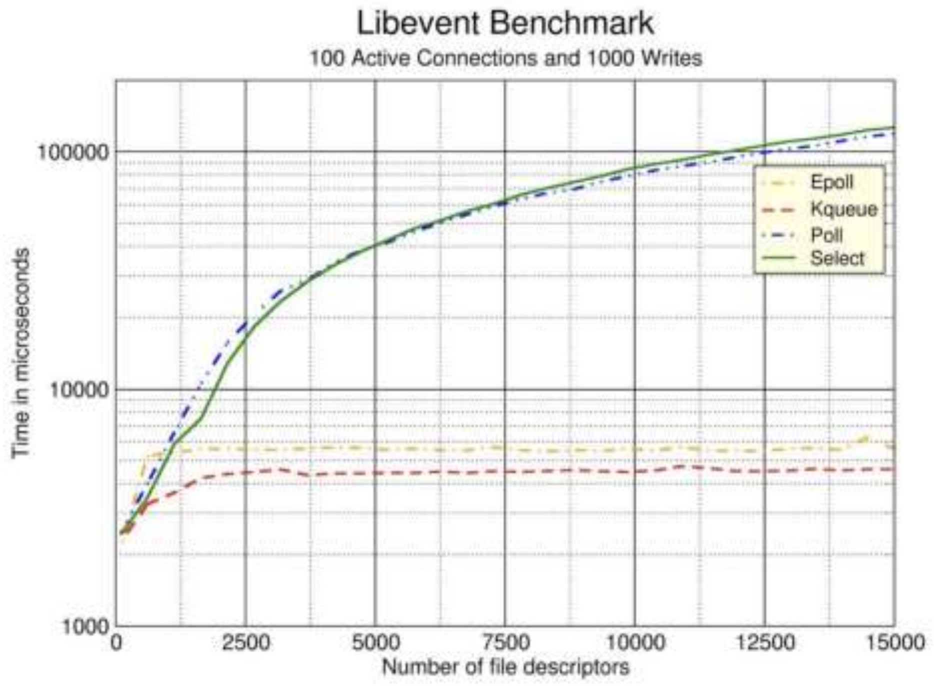
Concurrency matters

- “Good” concurrency model achieves **high throughput**, **low latency**, and **efficient resource utilization**.
- Fine-tailored model can improve performance by an order of magnitude or more.



What are the problems with existing multi-threading concurrency model?

- **Nondeterministic, resulting in uncertain access order of shared resources.**
  - **Synchronization**
  - **Atomics**
  - **…**

What are the problems with existing multi-threading concurrency model?

- **Incompatible with asynchronous I/O mechanism**
  - **Additional mechanisms(producer-consumer model, zero-copy, etc.)**
  - **Complicated asynchronous runtime**
  - **Extra syscall interfaces**
  - **Hard to code(manually implement event-loop or callback hell)**
  - **…**

I/O Multiplexing

- Select, Poll, Epoll
  - Need complicated data structure to maintain global I/O states.
    - Fd_set
    - Fd_queue
    - Red-black tree + ready queue
  - Expose extra syscall.
    - select
    - poll
    - epoll_create, epoll_ctl, epoll_wait,
- IOCP
  - Callback hell.

Userland task

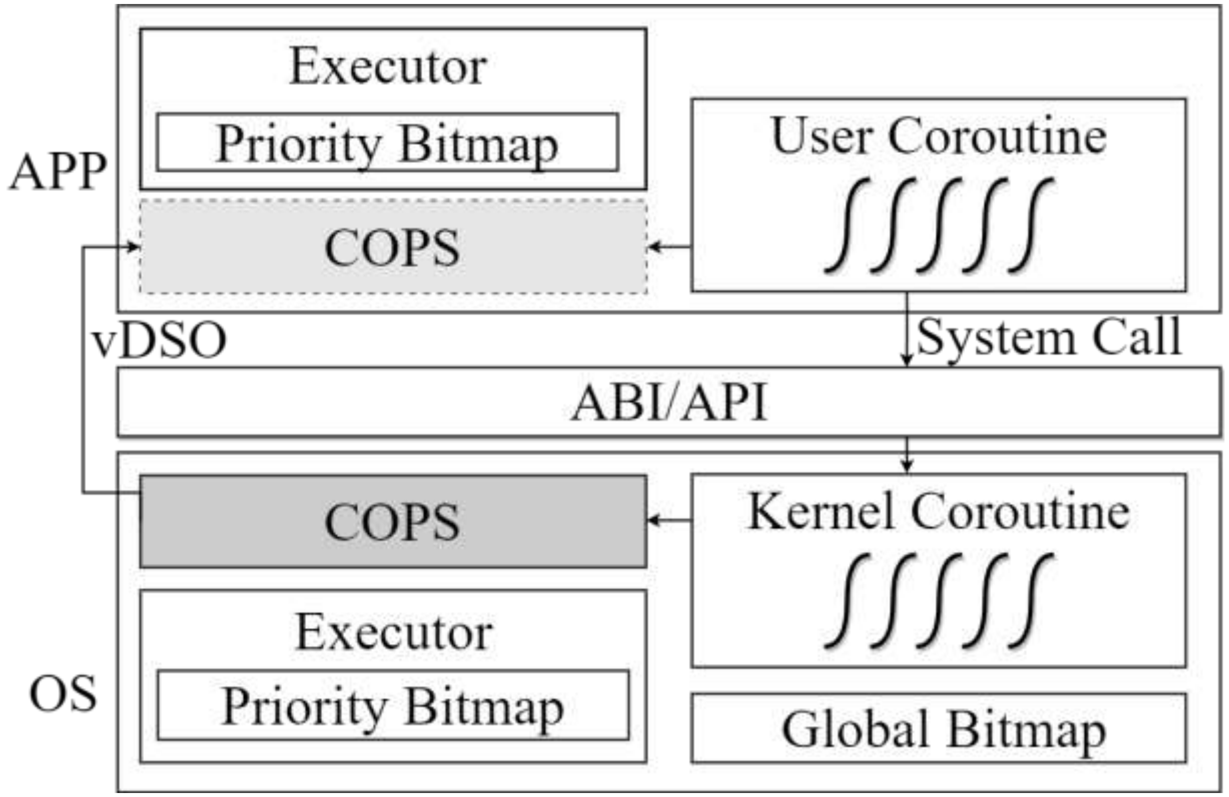
- POSIX AIO
  - **Without userland scheduling, os lacks awareness.**
  - **User thread management.**
  - **Frequent context switching across privilege levels.**

Solution: COPS

- Benefits from coroutines
  - Low cost of task switching.
  - Low resource usage.
  - Language facilities make programming easy.
- Treats coroutines as first-class citizens within OS
  - Introduces coroutines from user space into kernel.
  - Employs coroutine as the fundamental task unit to replace thread(decrease kernel complexity).
  - Offers a unified priority-based scheduling framework across kernel and user space(make kernel aware of userland task).
  - Supports asynchronous syscall(without extra syscall).

COPS Overview

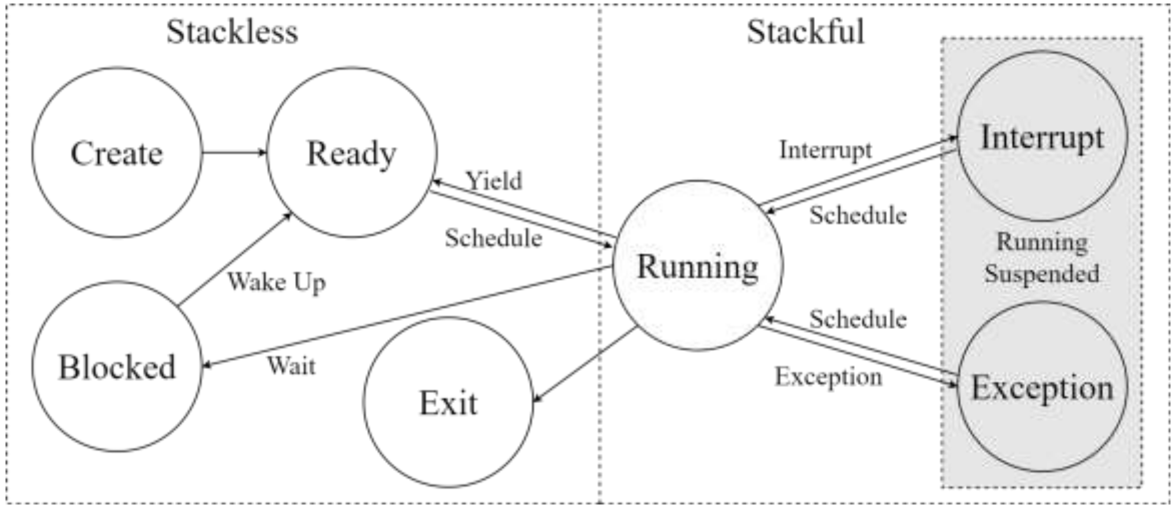
- **Separate executor for task management.**
- **Shared scheduling framework via vDSO.**
- **Priority bitmap for cooperative scheduling.**
- **Obtain asynchronous I/O service through syscall.**

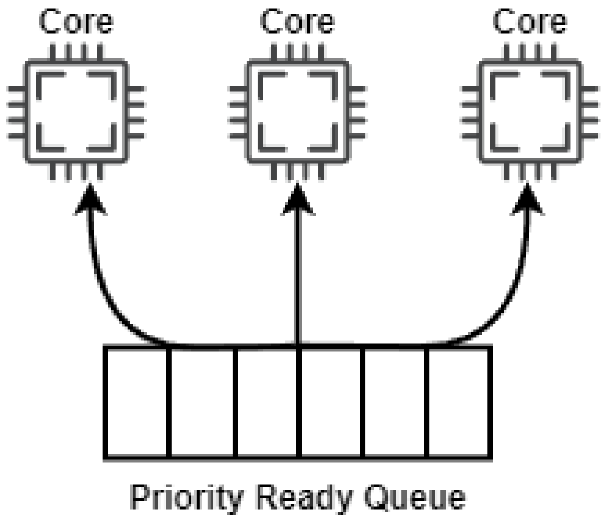


Coroutine Management

- **Coroutine Control Block**
- **Executor:**
  - **Priority ready queues**
  - **blocking set**
- **Coroutine state**

```rust
pub struct Coroutine{
    pub cid: CoroutineId,
    pub kind: CoroutineKind,
    pub priority: usize,
    pub future: Pin<Box<dyn Future<Output=()> + 'static + Send + Sync>>,
    pub waker: Arc<Waker>,
}
```

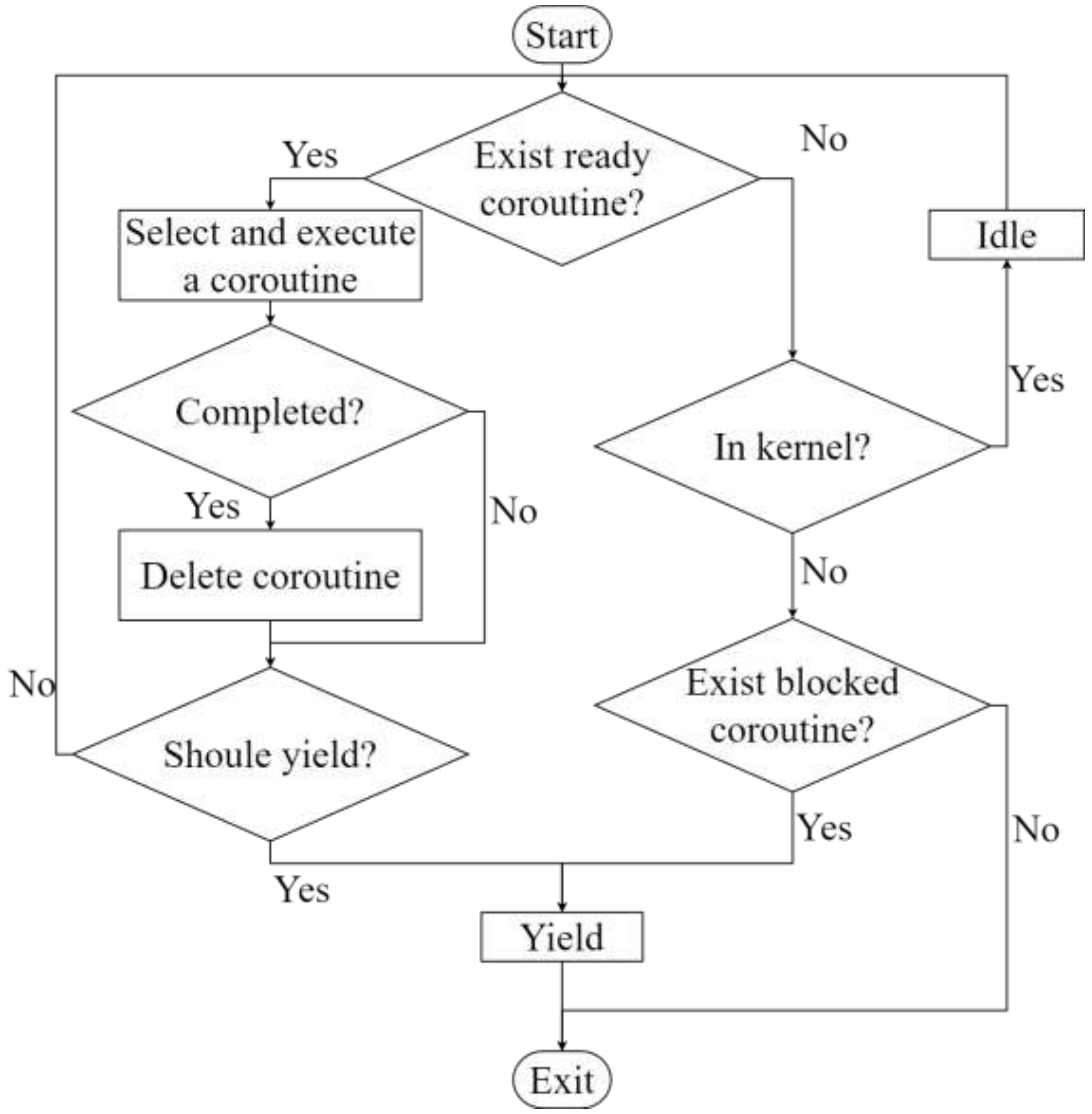




COPS API & Logic

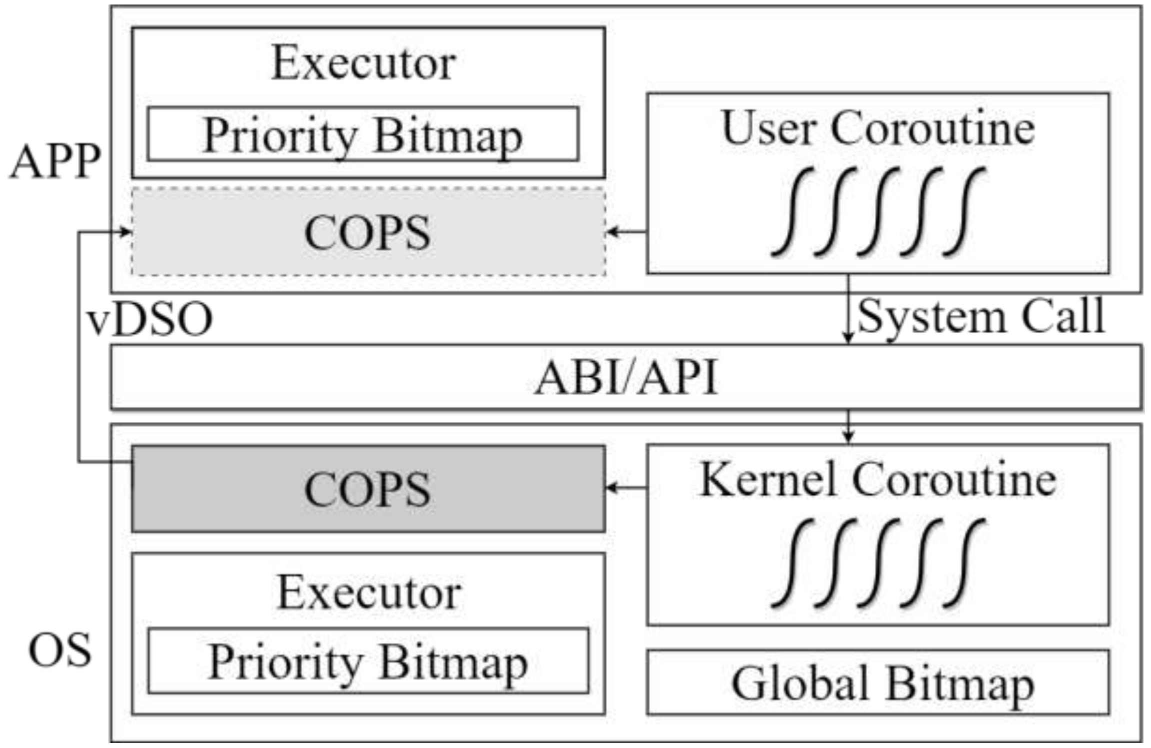
- **Just define task inner logic without concerning about task execution order.**

Function	Return value
spawn(future, priority)	cid
current()	cid
wake_up(cid)	
set_priority(cid, priority)	
alloc_cpu(cpu num)	



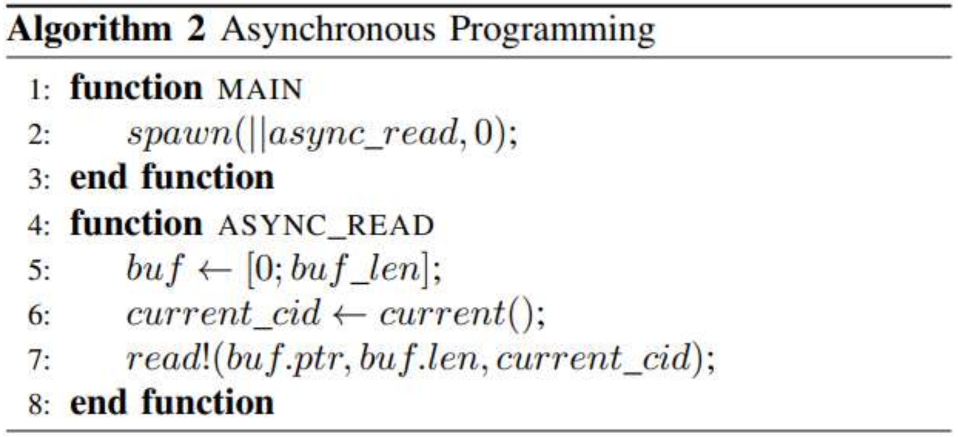
COPS's Global Cooperative Scheduling

- **Separative priority bitmap in executor for local cooperative scheduling.**
- **Global priority bitmap for global cooperative scheduling between kernel and user processes.**
    1. **Timer interrupt.**
    2. **Kernel scan local bitmaps.**
    3. **Kernel update global bitmap.**
    4. **Select the highest coroutine in all kernel and user processes.**



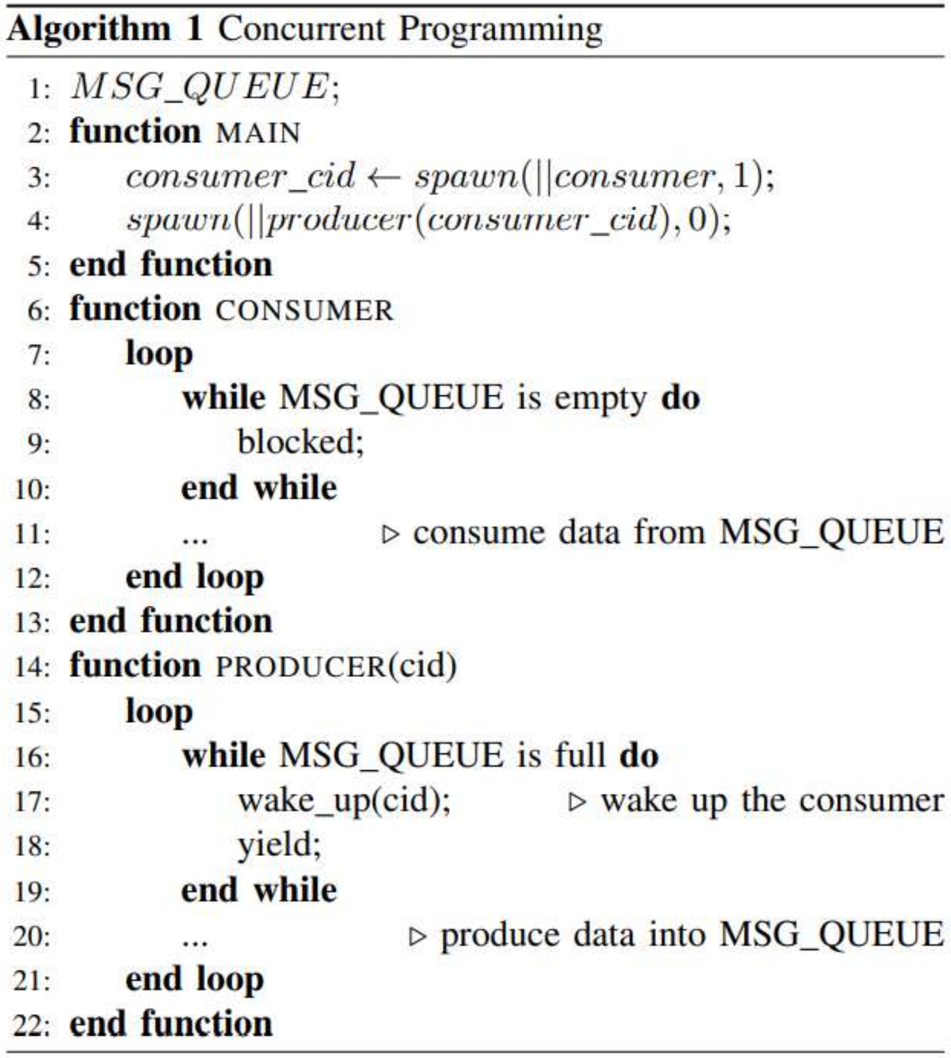
Usage Patterns of COPS

- **Concurrent Programming**
- **Asynchronous Programming**



Algorithm 2 Asynchronous Programming

```
function MAIN
    $spawn(||async\_read, 0)$;
end function
function ASYNC_READ
    $buf \leftarrow [0; buf\_len]$;
    $current\_cid \leftarrow current()$;
    $read!(buf.ptr, buf.len, current\_cid)$;
end function
```



Algorithm 1 Concurrent Programming

```
$MSG\_QUEUE$;
function MAIN
    $consumer\_cid \leftarrow spawn(||consumer, 1)$;
    $spawn(||producer(consumer\_cid), 0)$;
end function
function CONSUMER
    loop
        while MSG_QUEUE is empty do
            blocked;
        end while
        ...                         ▷ consume data from MSG_QUEUE
    end loop
end function
function PRODUCER(cid)
    loop
        while MSG_QUEUE is full do
            wake_up(cid);           ▷ wake up the consumer
            yield;
        end while
        ...                         ▷ produce data into MSG_QUEUE
    end loop
end function
```

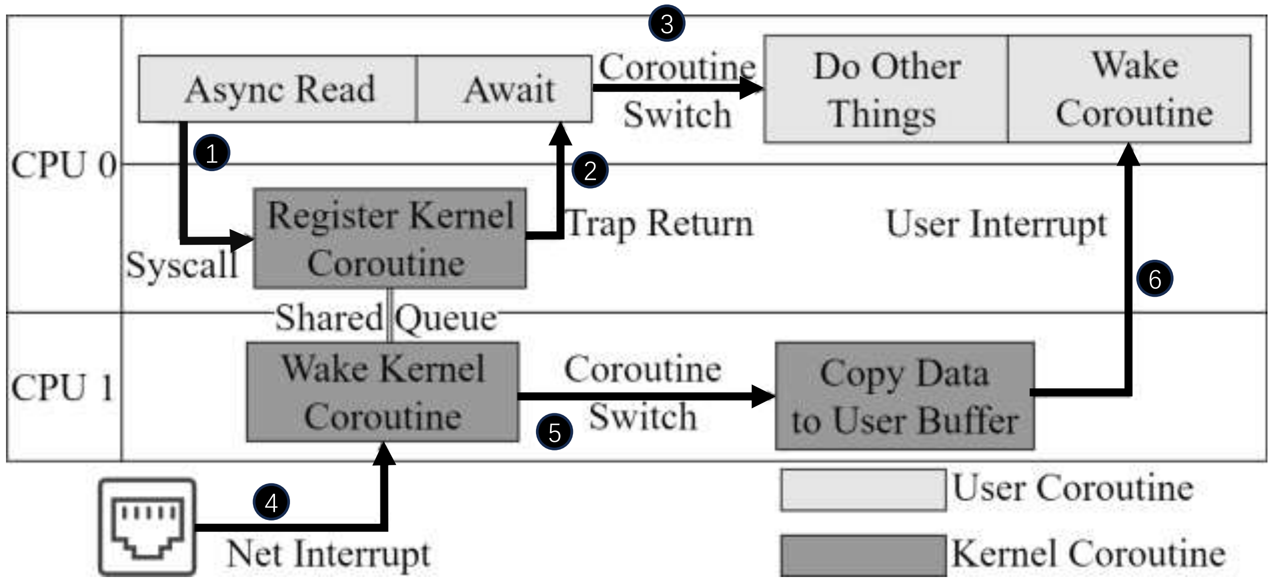
Asynchronous Syscall

CPU0

1. **App Issue asynchronous I/O request**
2. **Back to user space**
3. **Switch to do other things**

CPU1

4. **Receive net interrupt**
5. **Execute kernel coroutine**
6. **Wake up blocked task on CPU0**



Evaluation Questions

1. Can COPS outperform than multi-threading model?
    1. Throughput
    2. Latency
    3. Memory Usage
2. Are high priority requests handled first?

Evaluation Setup

- Testbed

Network Stack	smoltcp	
Operating System	rCore-tutorial	
FPGA	RISC-V soft IP core	rocket-chip with N extension, 4 Core, 100MHz
	Ethernet IP core	Xilinx AXI 1G/2.5G Ethernet Subsystem (1Gbps)
	Zynq UltraScale+ XCZU15EG MPSoC	

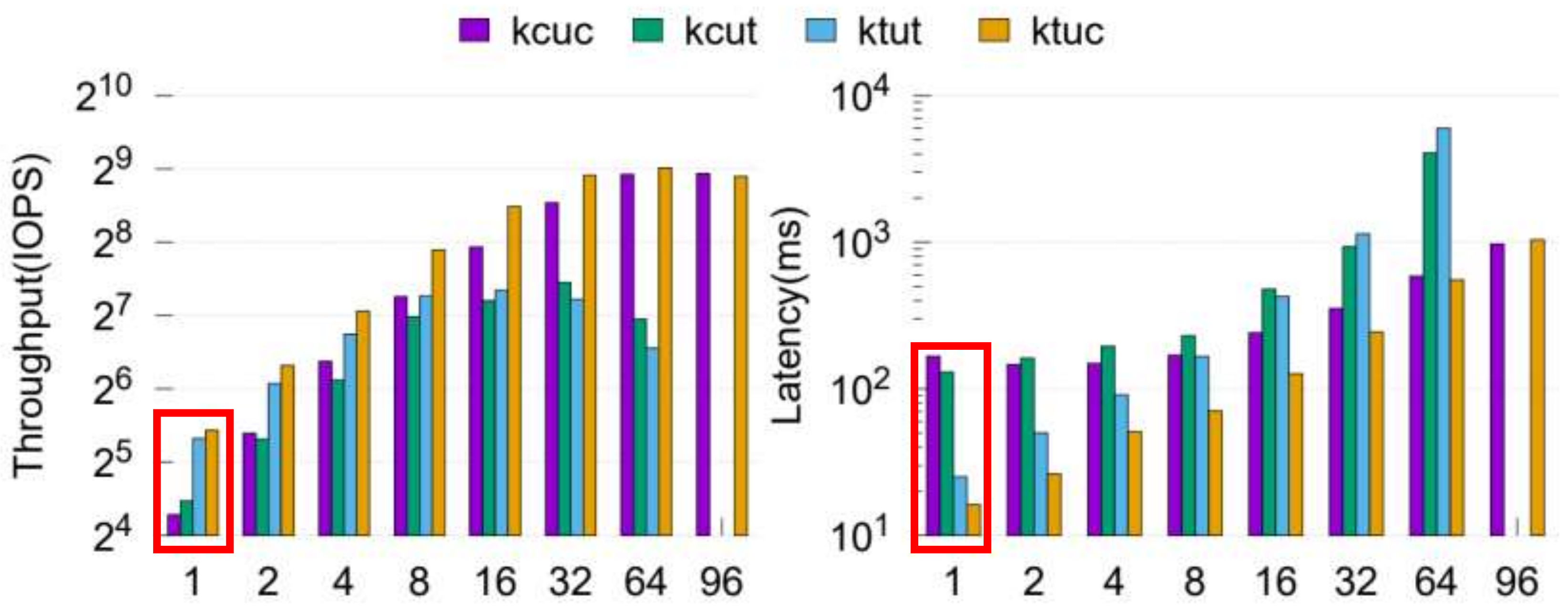
- Web Server built with three component(using Multi-threading / Coroutine)
  - Request receiver
  - Request handler
  - Response Sender

Evaluation: Thread vs. Coroutine

- Server: Kernel(**K**), User Process(**U**), Thread(**T**), Coroutine(**C**)
  - KCUC
  - KCUT
  - KTUT
  - KTUC: similar to select, poll, epoll
- Client
  - Package: 15*15 matrix payload
  - Interval: 100ms
  - 5 seconds

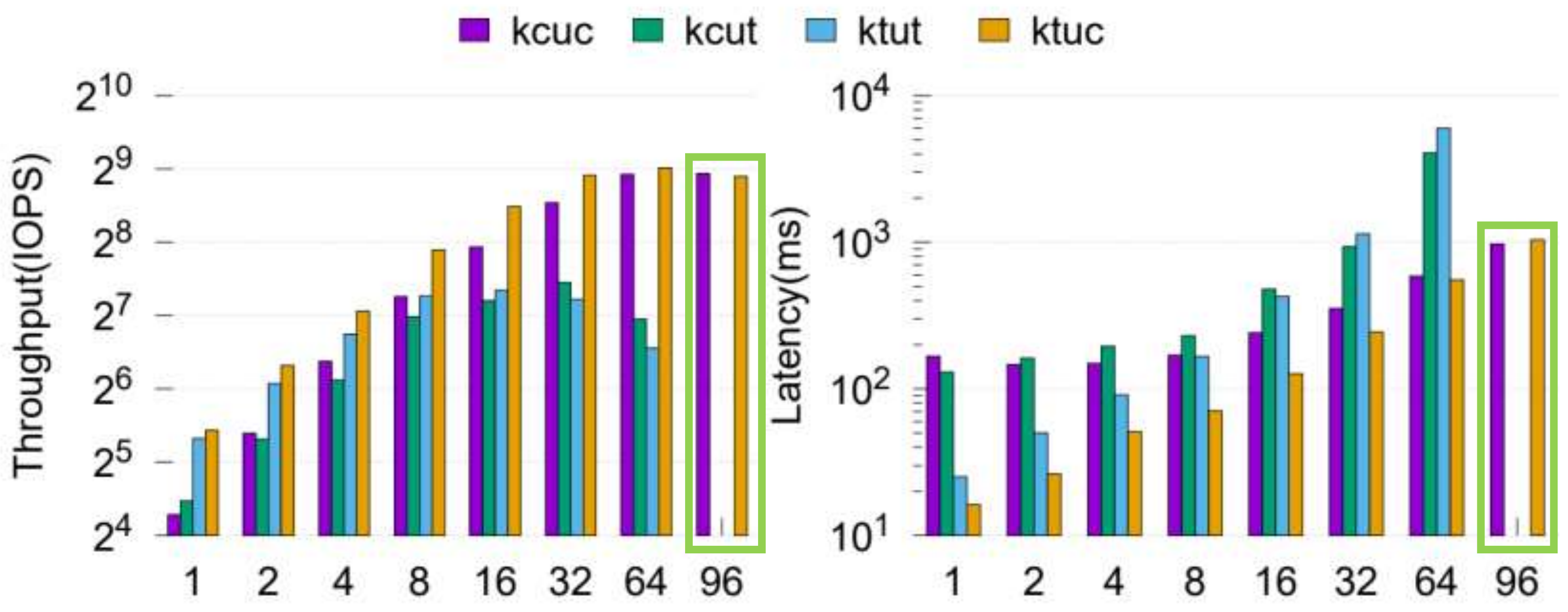
Evaluation: Coroutine vs. Thread

- Runtime overhead
  - Ready Queue across multiply cores is being lock-protected.
  - Extra core for light workload(as same core allocation as thread model).



Evaluation: Coroutine vs. Thread

- Suitable for heavy workload(KCUC vs. KTUC)
  - Higher throughput
  - Lower latency



Evaluation: Coroutine vs. Thread

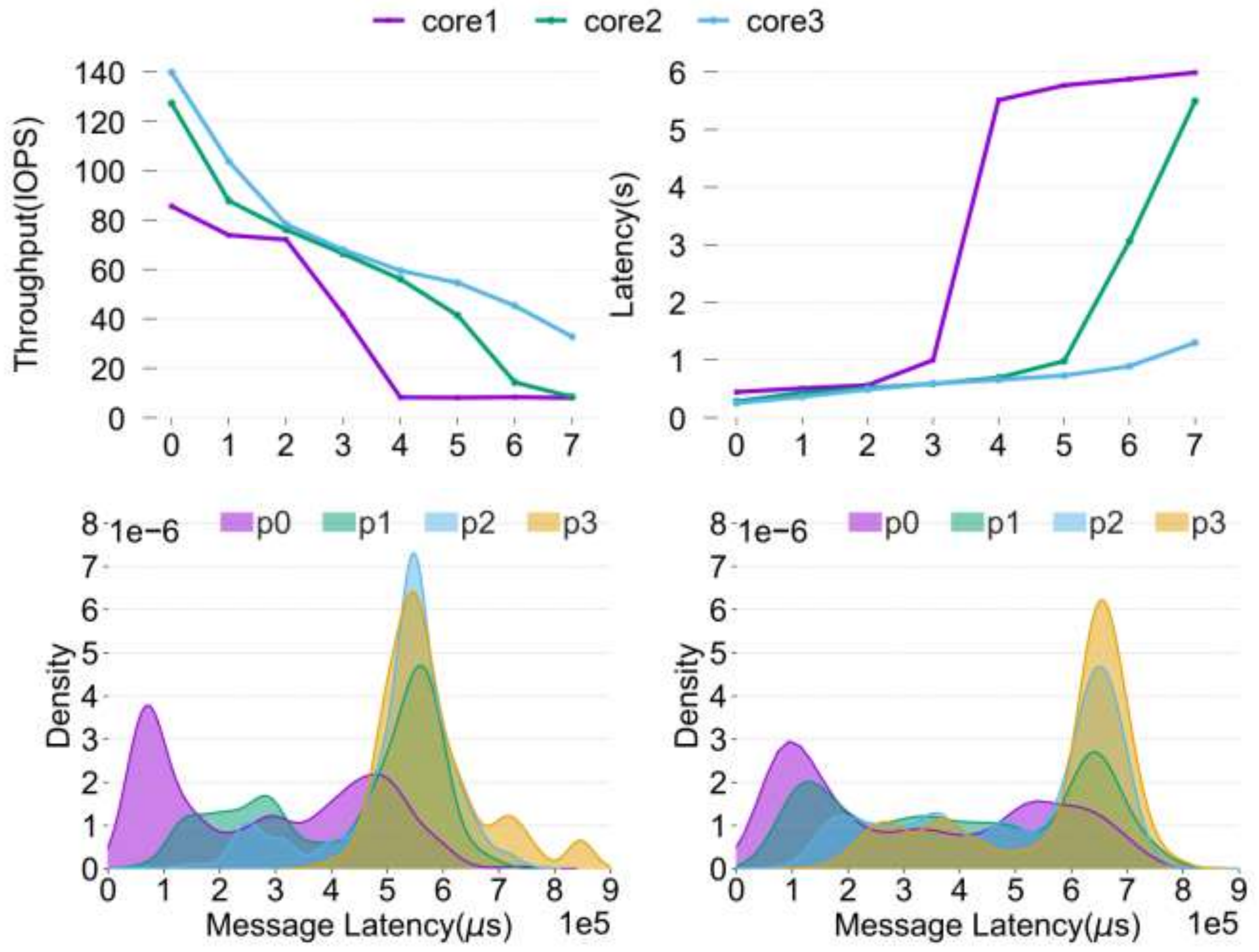
- Less memory usage(establish more connections at the same config)
  - Thread: each component need a kernel stack(0x4000 bytes) and a user stack(0x4000 bytes).
  - Coroutine:
    - receiver(120 bytes)
    - handler(64 bytes)
    - sender(80 bytes)
    - kernel syscall coroutine(176 bytes)

	Memory Usage(bytes)
KTUT	0x4000 ⋆ 2 ⋆ 3
KCUC	0x4000 ⋆ 2 + 176 + 120 + 80 + 64

Configuration	Size(bytes)	KCUC	KTUT
Kernel heap	0x80_0000	385	186
Kernel frame	0x1A0_0000		
User heap	0x20_0000		

Evaluation: Priority Orientation

- Setup
  - 64 connections across 8 priority
  - Interval: 50ms
  - 5 seconds
- Higher priority ->
  - Higher throughput + lower latency
- More resources ->
  - Lower priority connection is being improved.



(a) Core-2 (b) Core-4

Conclusion

COPS improve concurrency by:

- Treating coroutines as the first-class citizens within OS to benefit from coroutines.
- Employing priority scheduling to provide cooperation and efficient resource utilization.