A practical course on

Advanced systems programming in C/Rust

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Today's topic!

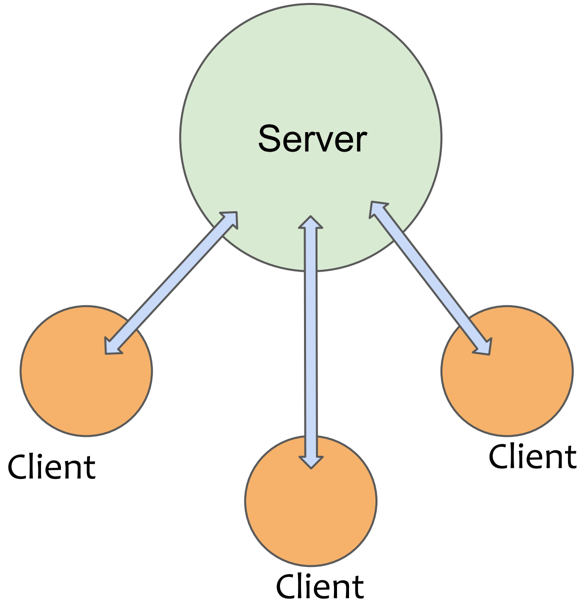
Network Programming

Outline

- Basics on networking
  - Fundamentals on communication
  - Networking protocols and the OSI layer
- Sockets
  - Stream/datagram sockets
  - Sockets API
  - Client/server example
- Server design
  - I/O multiplexing (select(), poll(), epoll())
  - Asynchronous I/O
- Tools
  - netstat, tcpdump
- Userspace networking

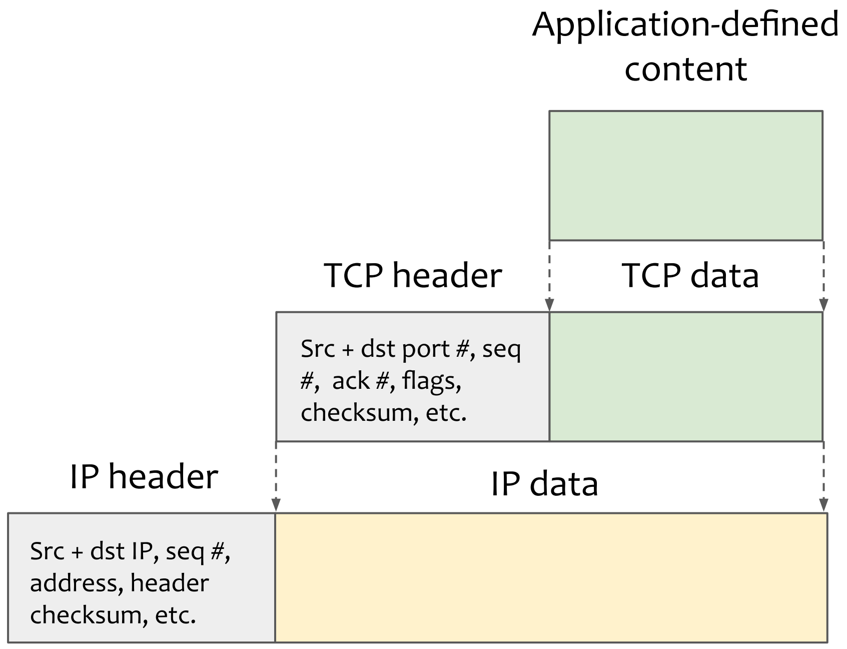
Fundamentals - Client/server model

- Server
  - Usually a long running process (*daemon process*)
  - Manages some resources
  - Receives and processes requests
- Client
  - Sends one or more requests to the server
  - Waits for the server's reply
- Transport layer
  - Network medium
  - Transfers the data



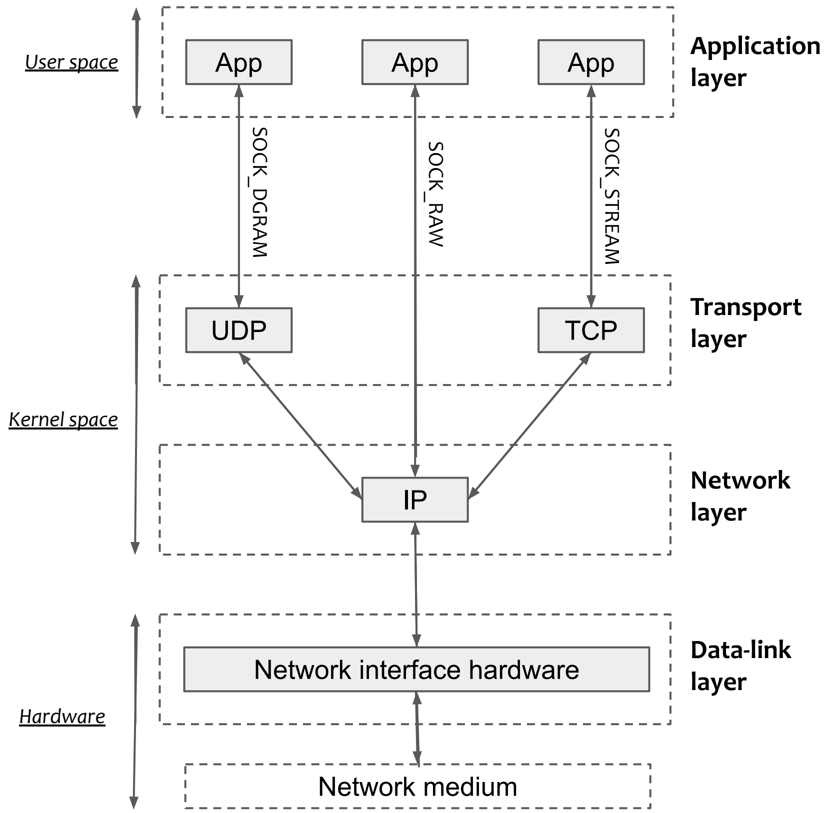
Networking Protocols and the OSI Layer

- Networking protocols:
  - Set of rules for data transmission
  - TCP/IP protocol (best-effort protocol)
- OSI layer:
  - Encapsulation
  - Application programmers only pass the data down
  - Sockets is the API to access the transport layer functions


Application-defined content
TCP header
TCP data
Src + dst port #, seq #, ack #, flags, checksum, etc.
IP header
IP data
Src + dst IP, seq #, address, header checksum, etc.

Data-link and Network Layers

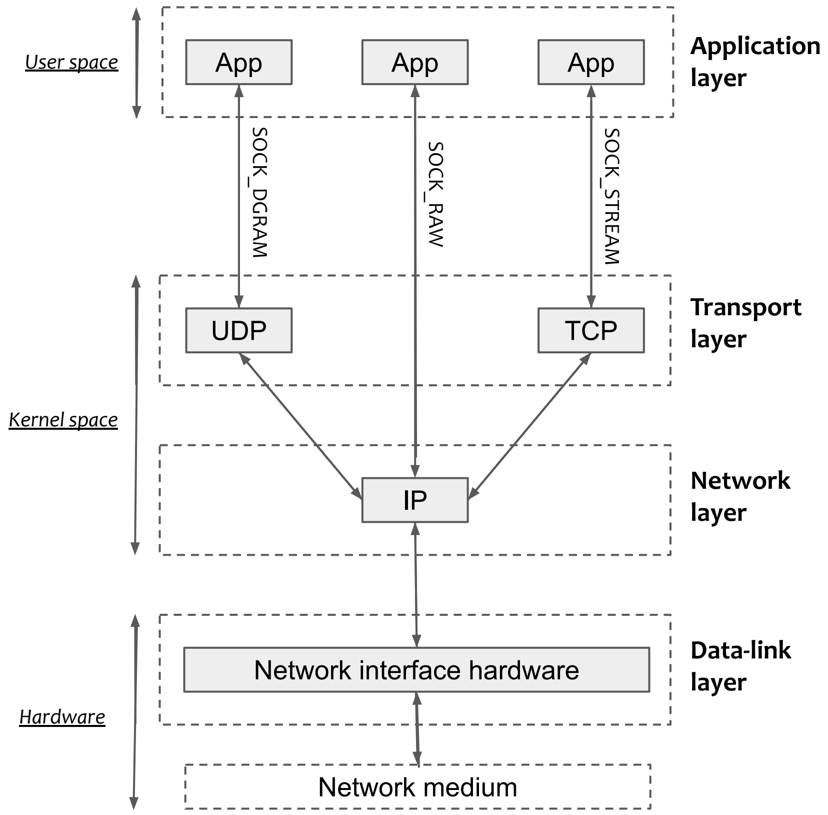
- Data-link layer
  - Device drivers and network card
  - Transfers frames
  - Maximum transmission unit (MTU)
- Network layer (IP)
  - Transfers packets (fragmentation, routing, etc.)
  - Connectionless and unreliable (best-effort)



Stream/Datagram Sockets

- Stream sockets
  - Implemented on top of TCP
  - Reliable, bidirectional, **byte-stream** communication channel

- Datagram sockets
  - Implemented on top of UDP
  - Not reliable; messages might be lost, duplicated or re-ordered
  - The receiver will drop the datagram in case of a queue overflow

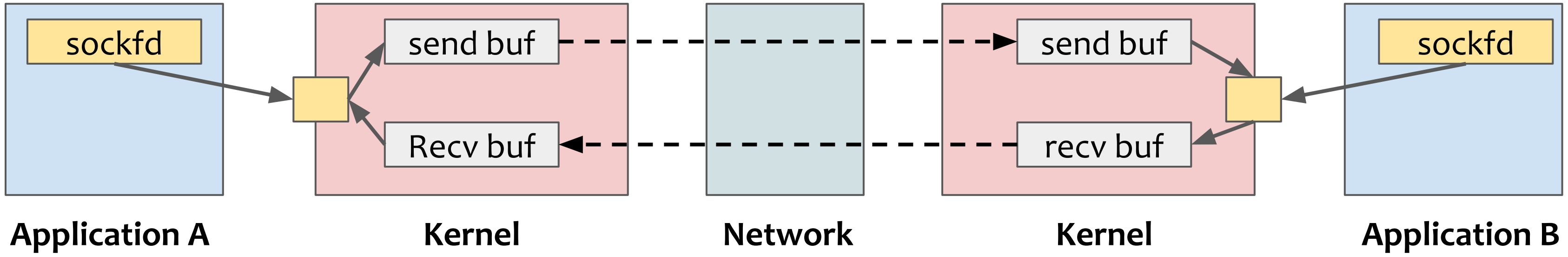


Sockets API

syscall	Description
socket()	Create a new communication endpoint
bind()	Attach a local address to a socket
listen()	Mark the socket as passive; can accept incoming connections
accept()	Accept a received connection request
connect()	Actively attempt to establish a connection
send(), sendto(), write()	Send **some** data over the connection
recv(), recvfrom(), read()	Receive **some** data over the connection
close()	Release the connection

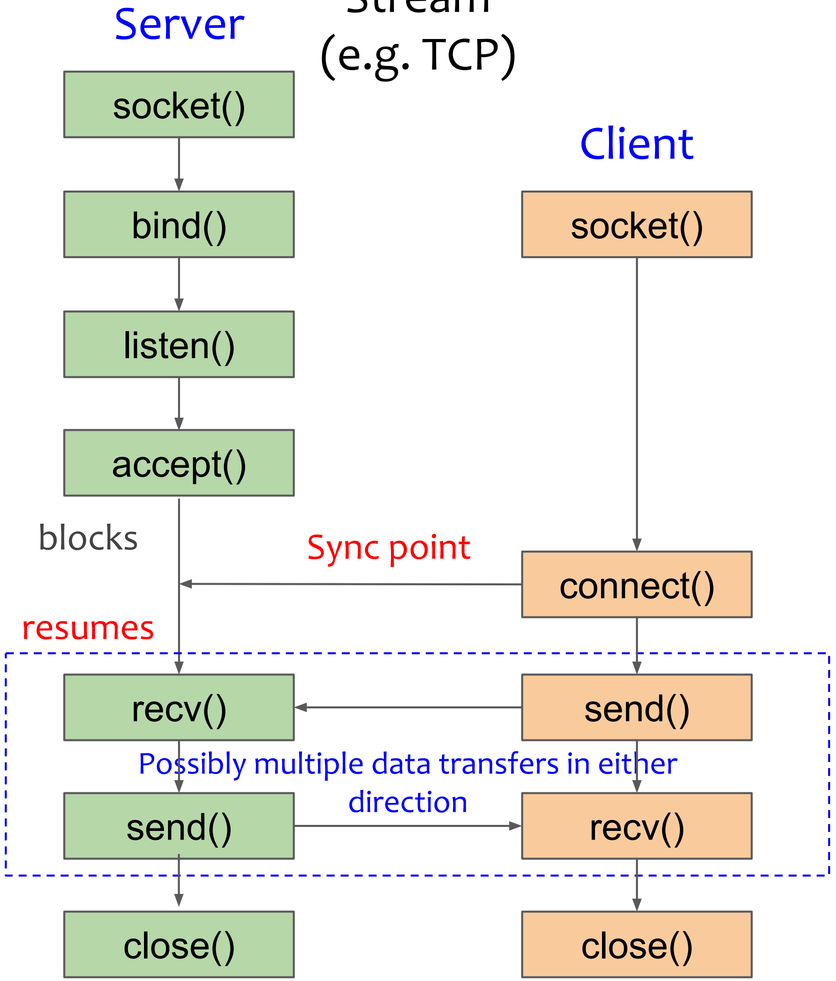
What is a socket in the end?

- An endpoint of communication (kernel)
- A file descriptor that lets us read/write data to network (application)

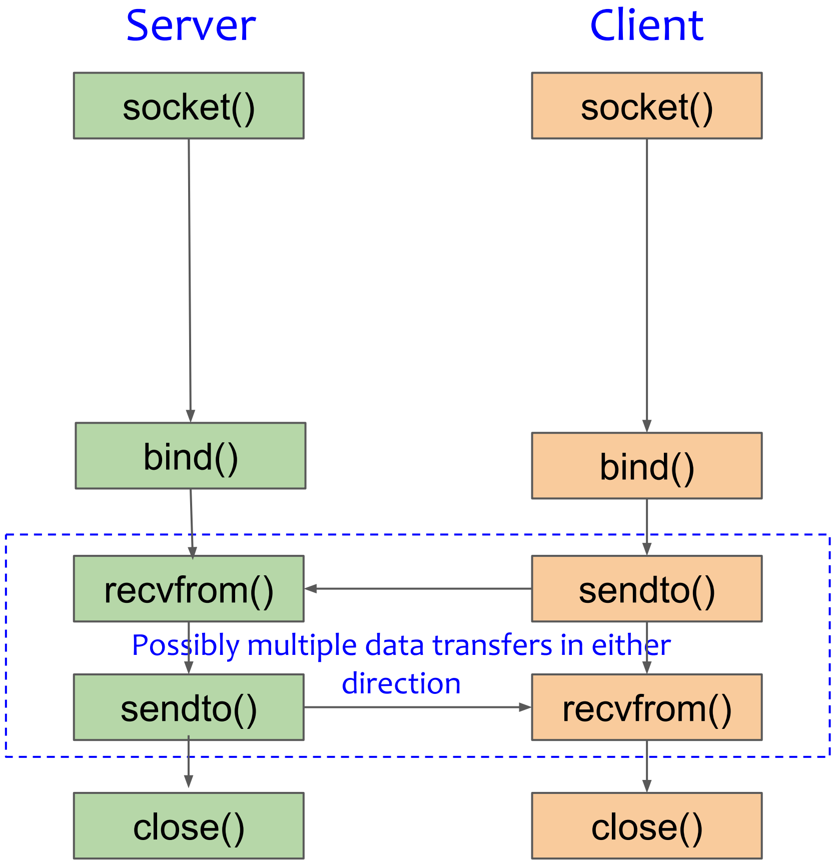


- Client/server communication is nothing more than reading and writing to socket descriptors
- Main distinction between regular file I/O and socket I/O is how application “opens” socket descriptors

Stream (e.g. TCP)



Datagram (e.g. UDP)



Non-blocking Sockets and Asynchronous I/O

- Blocking I/O is convenient but not sufficient;
  - Multiple connections
  - Simultaneous sends/receives
  - Simultaneously doing other-work

- Non-blocking sockets
  - If an operation is going to block, return failure (-1)
  - fcntl(), MSG_DONTWAIT, etc.
  - Require polling

- Asynchronous I/O
  - OS signals the applications when a syscall is completed
  - io_uring, std::async(), std::launch(), boost::asio library, etc.

Server design (1/2)

- Iterative server
  - Handles **one client** at a time
  - Clients might experience long delays
  - Example: iPerf, etc.

- Multitasking server□
  - A per-client process/thread
  - Allows parallelism
  - Process/threads incur overhead□s (e.g. creation, scheduling, context switching□, etc.)
  - Not scalable
  - Examples: apache httpd server, MySQL, etc.

- Multiplexing I/O
  - Supports more than one I/O channels
  - Each thread/process handles more than one connections
  - Requires non-blocking sockets to be effective
  - select(), poll()
  - Examples: nginx, nodejs, redis, etc.

Server design (2/2)

- select()*, poll()*
  - Monitors multiple file descriptors to see if I/O is possible on any of them
  - Blocks until one of the descriptors is ready or until timeouts
  - □Returns which descriptors are ready for reading/writing
- epoll()*
  - Similar to poll() but faster and scales better
  - Can also be used either as an edge-triggered or a level-triggered interface:
    - edge-triggered mode: a call to epoll_wait() returns only when a new event is enqueued with the epoll object
    - level-triggered mode: epoll_wait() returns as long as the condition holds
    - **Example**: a pipe registered with epoll receives data. A call to epoll_wait() will return. The reader only consumes some data from the buffer.
      - level-triggered mode: further calls to epoll_wait() return immediately
      - edge-triggered mode: epoll_wait() will return only once new data is written

* *for more info check the man pages*

Network Byte Order and Data Representation

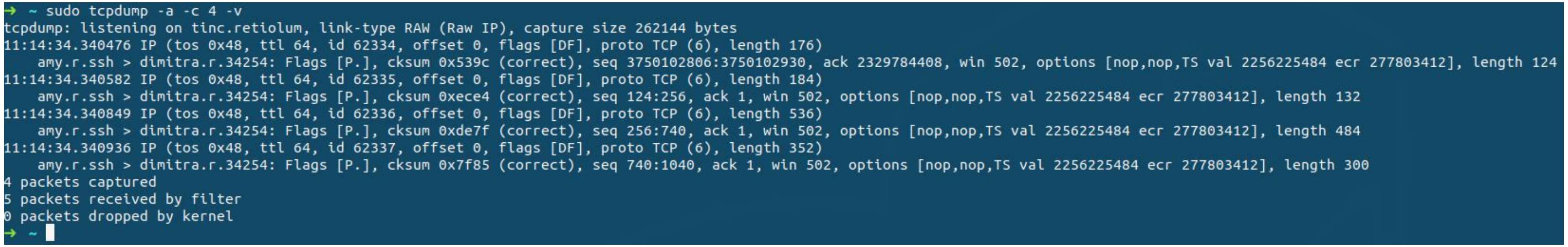
- Network byte order
  - Different machines/OSes have different word orderings; little-endian (lower bytes first), big-endian (higher bytes first)
  - The byte ordering used by **the network is always big-endian**
  - htonl(), htons(), ntohl(), ntohs()

- Data representation
  - Heterogeneous architectures/applications
  - Encode text (marshalling)
  - Serialization protocol (google protobufs, etc.)

- Internet socket addresses
  - IPv4 vs IPv6

Tools (1/3)

- tcpdump
  - Monitor traffic on a network
  - Example: dump (any) 4 packets and then exit (verbose on)

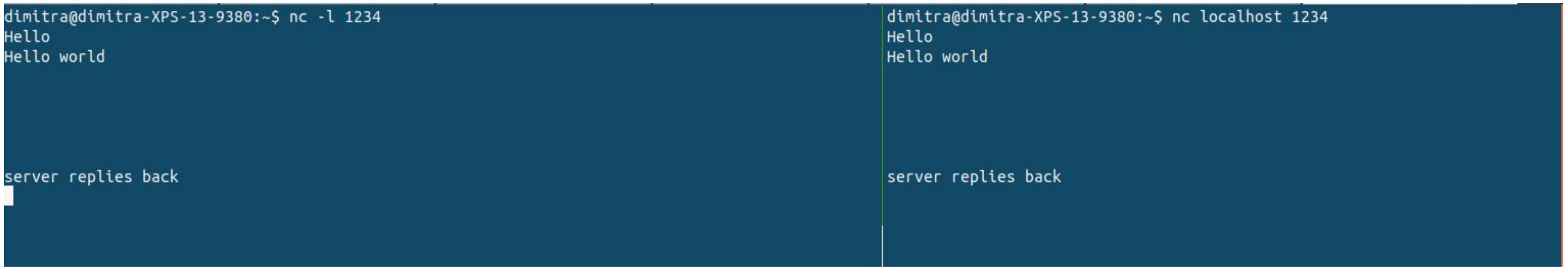


```
→ ~ sudo tcpdump -a -c 4 -v
tcpdump: listening on tinc.retiolum, link-type RAW (Raw IP), capture size 262144 bytes
11:14:34.340476 IP (tos 0x48, ttl 64, id 62334, offset 0, flags [DF], proto TCP (6), length 176)
    amy.r.ssh > dimitra.r.34254: Flags [P.], cksum 0x539c (correct), seq 3750102806:3750102930, ack 2329784408, win 502, options [nop,nop,TS val 2256225484 ecr 277803412], length 124
11:14:34.340582 IP (tos 0x48, ttl 64, id 62335, offset 0, flags [DF], proto TCP (6), length 184)
    amy.r.ssh > dimitra.r.34254: Flags [P.], cksum 0xece4 (correct), seq 124:256, ack 1, win 502, options [nop,nop,TS val 2256225484 ecr 277803412], length 132
11:14:34.340849 IP (tos 0x48, ttl 64, id 62336, offset 0, flags [DF], proto TCP (6), length 536)
    amy.r.ssh > dimitra.r.34254: Flags [P.], cksum 0xde7f (correct), seq 256:740, ack 1, win 502, options [nop,nop,TS val 2256225484 ecr 277803412], length 484
11:14:34.340936 IP (tos 0x48, ttl 64, id 62337, offset 0, flags [DF], proto TCP (6), length 352)
    amy.r.ssh > dimitra.r.34254: Flags [P.], cksum 0x7f85 (correct), seq 740:1040, ack 1, win 502, options [nop,nop,TS val 2256225484 ecr 277803412], length 300
4 packets captured
5 packets received by filter
0 packets dropped by kernel
→ ~
```

  - Filter packets (e.g. filters based on the src or dst IP, hostname, port, protocol, etc.)
  - Option `-A` to monitor packet content, etc.

Tools (2/3)

- netcat
  - Anything about TCP/UDP and UNIX-domain sockets
  - Example: bidirectional TCP Server/client
    - Server listens to localhost:1234
    - Client establishes a connection to localhost:1234



```
dimitra@dimitra-XPS-13-9380:~$ nc -l 1234
Hello
Hello world




server replies back
```

```
dimitra@dimitra-XPS-13-9380:~$ nc localhost 1234
Hello
Hello world




server replies back
```

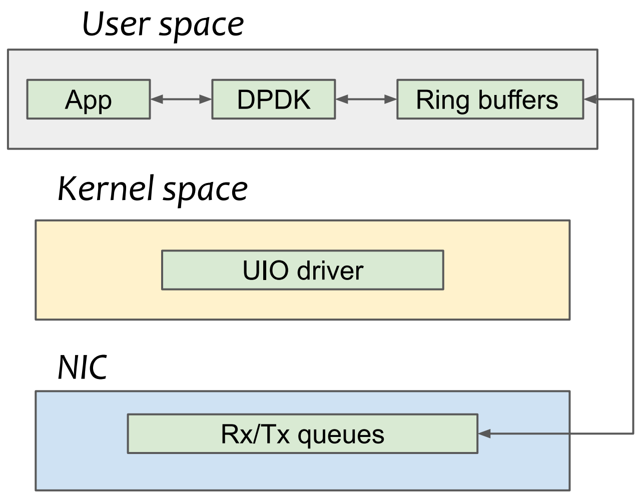
  - Open TCP connections, send UDP packets, listen on TCP/UDP ports, port scanning, etc.
  - Example: nc -v -n <IP> <port range>

Tools (3/3)

- More complex protocols
  - tshark/Wireshark

Userspace networking

- Sockets cross the kernel
    - Overheads due to privilege checking, cpu mode switch, data moving, etc.
- Networking libraries that bypass the kernel
    - DPDK, RDMA, etc.



Assignment

Tasks:

- Implement your own client/server application!
- Make use of socket API to design a multiplexing I/O server.
    - Non-blocking sockets, select(), send(), recv(), etc.
- Make use of google::protobufs as a serialization protocol for the messages.

Thank you for listening!

See you in the Q&A session