L41 - Lecture 5: The Network Stack (1)

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Reminder: where we left off in Lent Term

Long, long ago, but in a galaxy not so far away:

- Lecture 3: The Process Model (1)
- Lecture 4: The Process Model (2)
- Lab 1: I/O performance
- Lab 2: IPC buffer size and probe effect
- Lab 3: Micro-architectural effects of IPC

Explore several (implied, and it turns out, incorrect) hypotheses:

- Larger I/O and IPC buffer sizes amortize system-call overheads, improving application performance
- Micro-architecture is irrelevant
- The probe effect doesn't matter in real workloads

A key OS function: networking

- Communication between distributed computer systems
    - *Local-area networking* (LANs) and *wide-area networking* (WANs)

- A network stack provides:
    - Sockets API and extensions
    - Interoperable, feature-rich, high-performance protocol implementations (e.g., IPv4, IPv6, ICMP, UDP, TCP, SCTP, ...)
    - Device drivers for Network Interface Cards (NICs)
    - Monitoring and management interfaces (BPF, `ioctl`)
    - Plethora of support libraries (e.g., DNS)

- Dramatic changes over 30 years:
    - 1980s: Early packet-switched networks, UDP+TCP/IP, Ethernet
    - 1990s: Large-scale migration to IP; Ethernet VLANs
    - 2000s: 1-Gigabit/s, then 10-Gigabit/s Ethernet; 802.11, GSM data
    - 2010s: Large-scale deployment of IPv6; 40/100-Gigabit/s Ethernet
- Vanishing technologies: UUCP, IPX/SPX, ATM, token ring, SLIP, ...

The Berkeley Sockets API

```
close()
read()
write()
...

accept()
bind()
connect()
getsockopt()
listen()
recv()
select()
send()
setsockopt()
socket()

...
```

- Universal API for TCP/IP (POSIX, Windows, ...)
- *The Design and Implementation of the 4.3BSD Operating System* (although appeared in 4.2)
- Kernel-resident network stack serving userspace networking applications via system calls
- Reuse file-descriptor abstraction
  - Same API for local and distributed IPC
  - Simple, synchronous, copying semantics
  - Blocking/non-blocking I/O, `select()`
- Multi-protocol (e.g., IPv4, IPv6, ISO, ...)
  - TCP-focused but not TCP-specific
  - Cross-protocol abstractions: ‘protocol’, ‘socket address’, ‘stream’, ‘datagram’, ...
- NB: ‘socket’ in BSD API is not the same as a ‘socket’ in the TCP RFC

Early BSD network-stack design principles

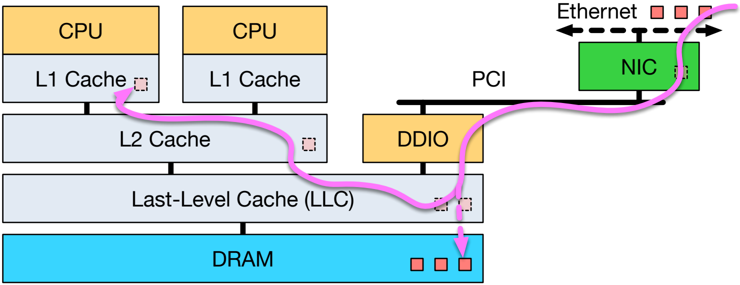
- Framework for network research
- Object-oriented: multiple protocols, multiple socket types, one API
    - Protocol-independent: streams vs. datagrams, sockets, socket buffers, socket addresses, network interfaces, routing table, packets
    - Protocol-specific: connection lists, address/routing specialization, routing, transport protocol itself – encapsulation, decapsulation, etc.
- Fundamentally packet-oriented:
    - Packets and packet queueing as fundamental primitives
    - If there is a failure (overload, corruption) drop the packet
    - Work hard to maintain packet source ordering
    - Differentiate ‘receive’ from ‘deliver’ and ‘send’ from ‘transmit’
    - Heavy focus on TCP functionality and performance
    - Middle-node (forwarding), not just edge-node (I/O), functionality
    - High-performance packet capture (Berkeley Packet Filter (BPF))

FreeBSD network-stack design principles

All of the 1980s features and also ...

- Multi-processor scalability
- NIC offload features (checksums, TSO/LRO, full TCP)
- Multi-queue network cards with load balancing/flow direction
- Performance to 10s or 100s of Gigabit/s
- Dual-IPv4/IPv6
- Security/privacy: firewalls, IPsec, ...
- Flexible memory model integrates with VM for zero-copy
- Full network-stack virtualisation
- Userspace networking via `netmap`

Memory flow in hardware

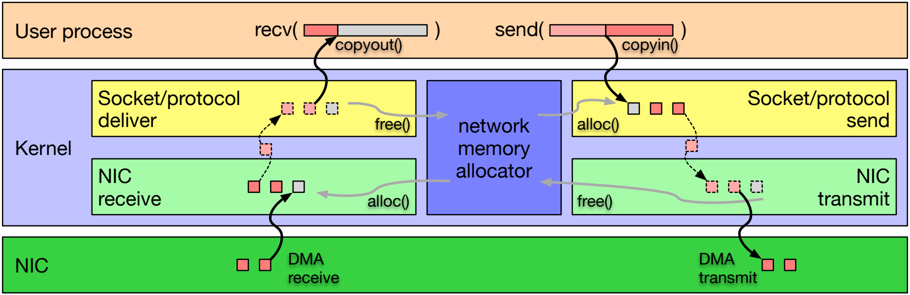


- Key idea: *follow the memory*

- Historically, memory copying in stack avoided due to CPU cost
- Today, memory copying in stack avoided due to cache footprint

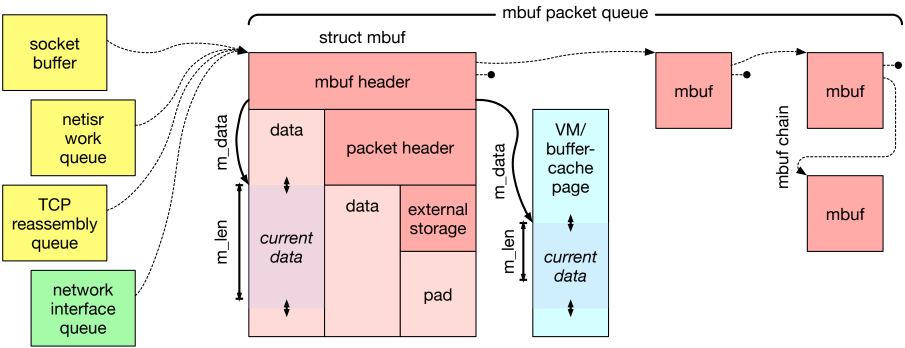
- Recent Intel CPUs push and pull DMA via the LLC (“DDIO”)
- NB: if we differentiate ‘send’ and ‘transmit’, is this a good idea?

Memory flow in software



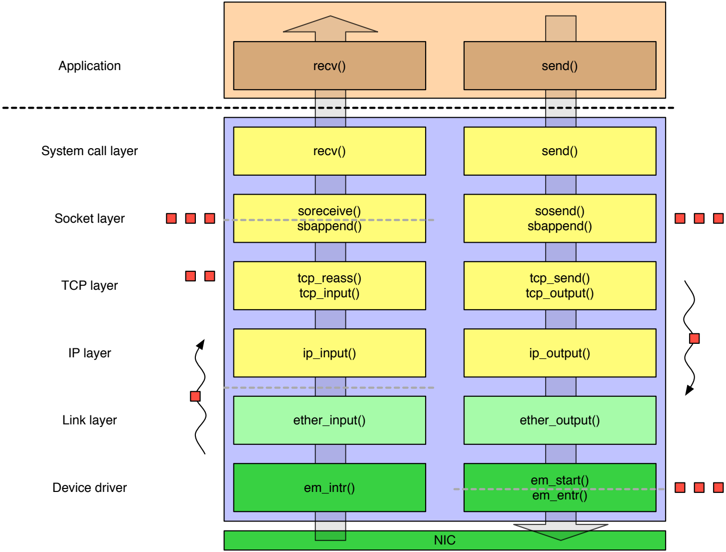
- Socket API implies one copy to/from user memory
  - Historically, zero-copy VM tricks for socket API ineffective
- Network buffers cycle through the slab allocator
  - Receive: allocate in NIC driver, free in socket layer
  - Transmit: allocate in socket layer, free in NIC driver
- DMA performs second copy; can affect cache/memory bandwidth
  - NB: what if packet-buffer working set is larger than the cache?

The `mbuf` abstraction

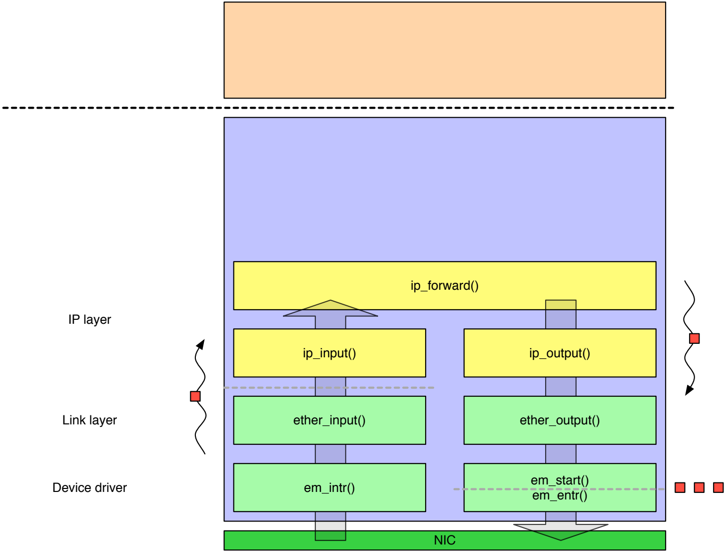


- `mbuf` chains represent in-flight packets, streams, etc.
  - Also a unit of *work* allocation throughout the stack
  - mbufs reference an in-`mbuf` or external buffer (e.g., VM page)
  - Bi-modal packet size distribution; e.g., TCP ACKs vs. data
  - Common operations: prepend, append, truncate at front or end
- Similar abstractions in other OSes – e.g., `skbuff` in Linux

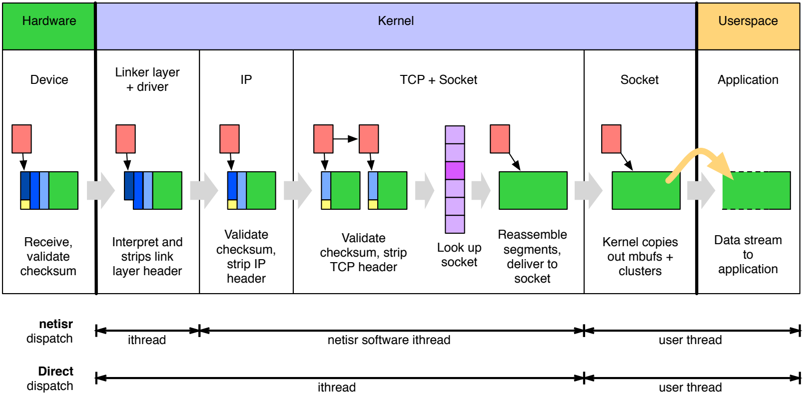
Local send/receive paths in the network stack



Forwarding path in the network stack

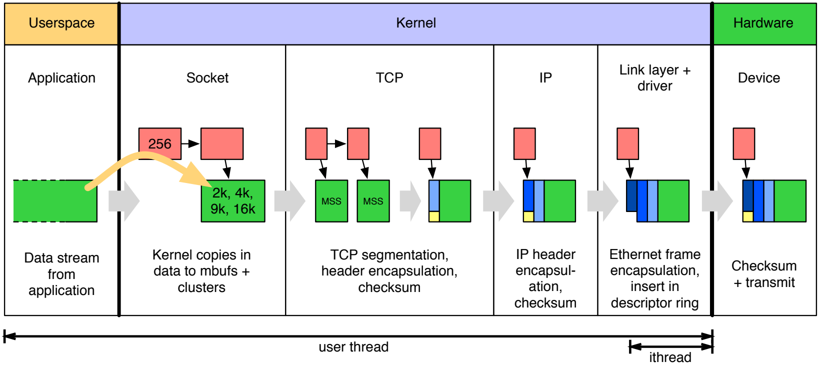


Work dispatch: input path



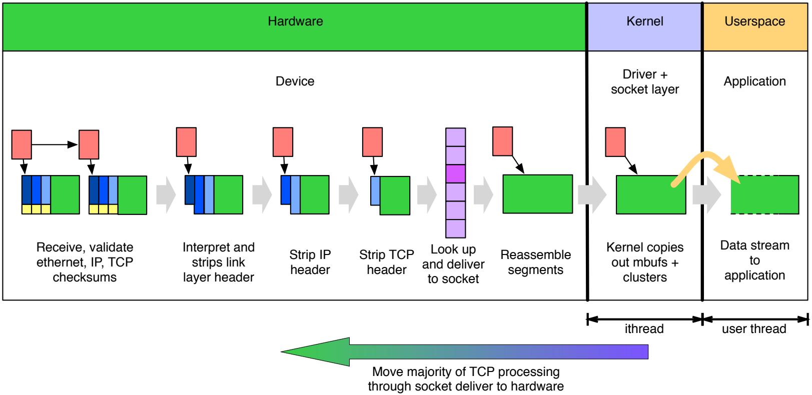
- Deferred dispatch - *ithread -> netisr thread -> user thread*
- Now: direct dispatch - *ithread -> user thread*
  - Pros: reduced latency, better cache locality, drop overload early
  - Cons: reduced parallelism and work placement opportunities

Work dispatch: output path



- Fewer deferred dispatch opportunities implemented
- Gradual shift of work from software to hardware
  - Checksum calculation, segmentation, ...
  - But no fundamental changes to output path

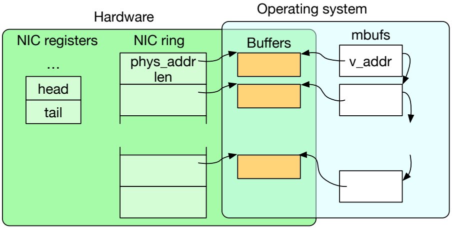
Work dispatch: TOE input path

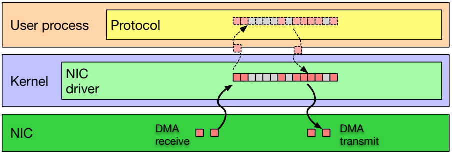


- Full TCP offload: kernel provides socket buffers and resource allocation
- Remainder, including state, retransmits, reassembly, etc, in NIC
  - But: Two network stacks? Less flexible/updateable structure?
- Better with an explicit SW architecture – e.g., Microsoft Chimney?

netmap: a novel framework for fast packet I/O

Luigi Rizzo, USENIX ATC 2012 (best paper).

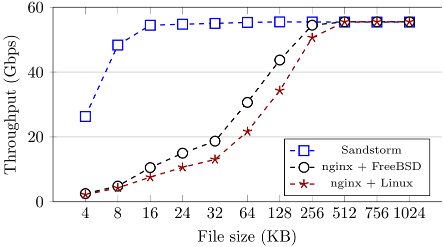


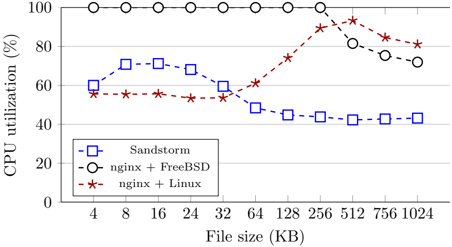


- Map NIC buffers directly into user process memory
- Zero copy to application
- Userspace network stack can be specialized to task (e.g., packet forwarding)
- System calls initiate DMA, block for NIC events
- Packets can be reinjected into normal stack
- Ships in FreeBSD, patch available for Linux

Network Stack Specialization for Performance

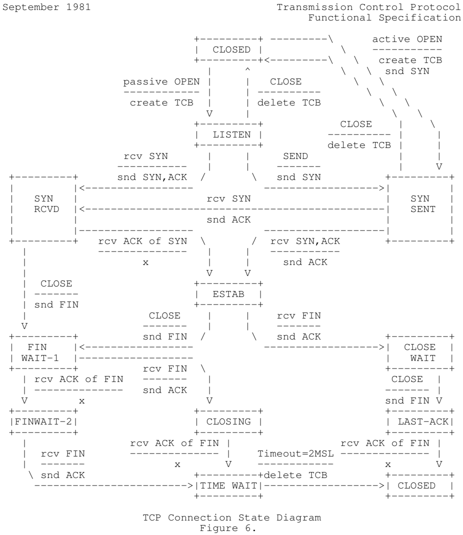
Ilias Marinos, Robert N.M. Watson, Mark Handley, SIGCCOMM 2014.





- 30 years since current network-stack architecture principles developed
- Massive changes in compilers, architecture, micro-architecture, memory, buses, NICs
  - Optimising compilers
  - Cache-centered CPUs
  - Multiprocessing, NUMA
  - DMA, multiqueue
  - 10 Gigabit/s Ethernet
- Revisit fundamentals through clean-slate stack

Next time: Socket buffers and TCP



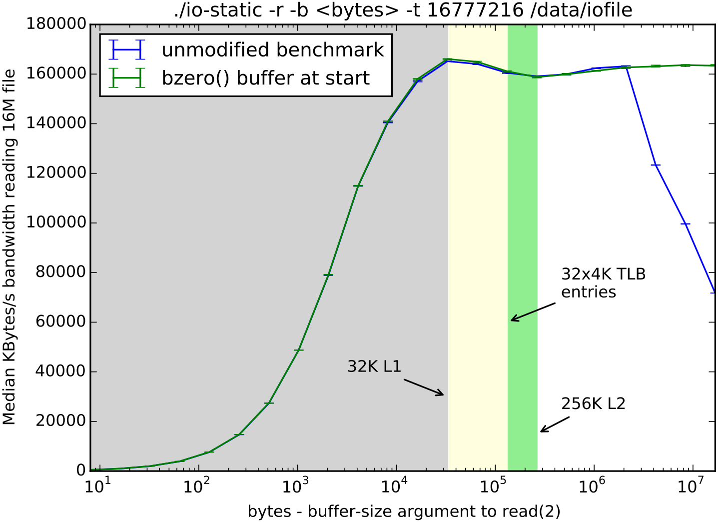
```
September 1981                              Transmission Control Protocol
                                                Functional Specification

                              +---------+ ---------\      active OPEN
                              |  CLOSED |            \    -----------
                              +---------+<---------\   \   create TCB
                                |     ^              \   \  snd SYN
                   passive OPEN |     |   CLOSE        \   \
                   ------------ |     | ----------       \   \
                    create TCB  |     | delete TCB         \   \
                                V     |                      \   \
                              +---------+            CLOSE    |    \
                              |  LISTEN |          ---------- |     |
                              +---------+          delete TCB |     |
                   rcv SYN      |     |     SEND              |     |
                  -----------   |     |    -------            |     V
 +---------+      snd SYN,ACK  /       \   snd SYN          +---------+
 |         |<-----------------           ------------------>|         |
 |   SYN   |                    rcv SYN                     |   SYN   |
 |   RCVD  |<-----------------------------------------------|   SENT  |
 |         |                    snd ACK                     |         |
 |         |------------------           -------------------|         |
 +---------+   rcv ACK of SYN  \       /  rcv SYN,ACK       +---------+
   |           --------------   |     |   -----------
   |                  x         |     |     snd ACK
   |                            V     V
   |  CLOSE                   +---------+
   | -------                  |  ESTAB  |
   | snd FIN                  +---------+
   |                   CLOSE    |     |    rcv FIN
   V                  -------   |     |    -------
 +---------+          snd FIN  /       \   snd ACK          +---------+
 |  FIN    |<-----------------           ------------------>|  CLOSE  |
 | WAIT-1  |------------------                              |   WAIT  |
 +---------+          rcv FIN  \                            +---------+
   | rcv ACK of FIN   -------   |                            CLOSE  |
   | --------------   snd ACK   |                           ------- |
   V        x                   V                           snd FIN V
 +---------+                  +---------+                   +---------+
 |FINWAIT-2|                  | CLOSING |                   | LAST-ACK|
 +---------+                  +---------+                   +---------+
   |                rcv ACK of FIN |                 rcv ACK of FIN |
   |  rcv FIN       -------------- |    Timeout=2MSL -------------- |
   |  -------              x       V    ------------        x       V
    \ snd ACK                 +---------+delete TCB         +---------+
     ------------------------>|TIME WAIT|------------------>| CLOSED  |
                              +---------+                   +---------+

                      TCP Connection State Diagram
                               Figure 6.
```

- McKusick, et al: Chapter 14 (*Transport-Layer Protocols*)
- The *socket buffer* abstraction
- A (very) little about the TCP implementation
- The TCP state machine
- TCP flow and congestion control
- The final two labs

Lab 1 - I/O - Buffer size vs. throughput



Lab 1 - I/O - Static/dynamic linking vs. throughput