L41 - Lecture 5: The Network Stack (1)

Dr Robert N. M. Watson

19 January 2016

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- Micro-architecture is irrelevant
- The probe effect doesn't matter in real workloads

This time: Introduction to the Network Stack

Rapid tour across hardware and software:

1. Networking and the sockets API
2. Network-stack design principles: 1980s and today
3. Memory flow across hardware and software
4. Network-stack construction and work flows
5. Recent network-stack research

Networking: a key OS function

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  - 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)
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  - 1990s: Large-scale migration to IP; Ethernet VLANs
  - 2000s: 1-Gigabit/s, then 10-Gigabit/s Ethernet; 802.11, GSM data
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- Vanishing technologies: UUCP, IPX/SPX, ATM, token ring, SLIP, ...

The Berkeley Sockets API (1983)

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write()
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- Reuse file-descriptor abstraction
  - Same API for local and distributed IPC
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- Multi-protocol (e.g., IPv4, IPv6, ISO, ...)
  - TCP-focused but not TCP-specific
  - Cross-protocol abstractions and libraries
  - Protocol-specific implementations
  - “Portable” applications

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  - High-performance packet capture: Berkeley Packet Filter (BPF)

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- Hardware:
  - Multi-processor scalability
  - NIC offload features (checksums, TSO/LRO, full TCP)
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  - Performance to 10s or 100s of Gigabit/s
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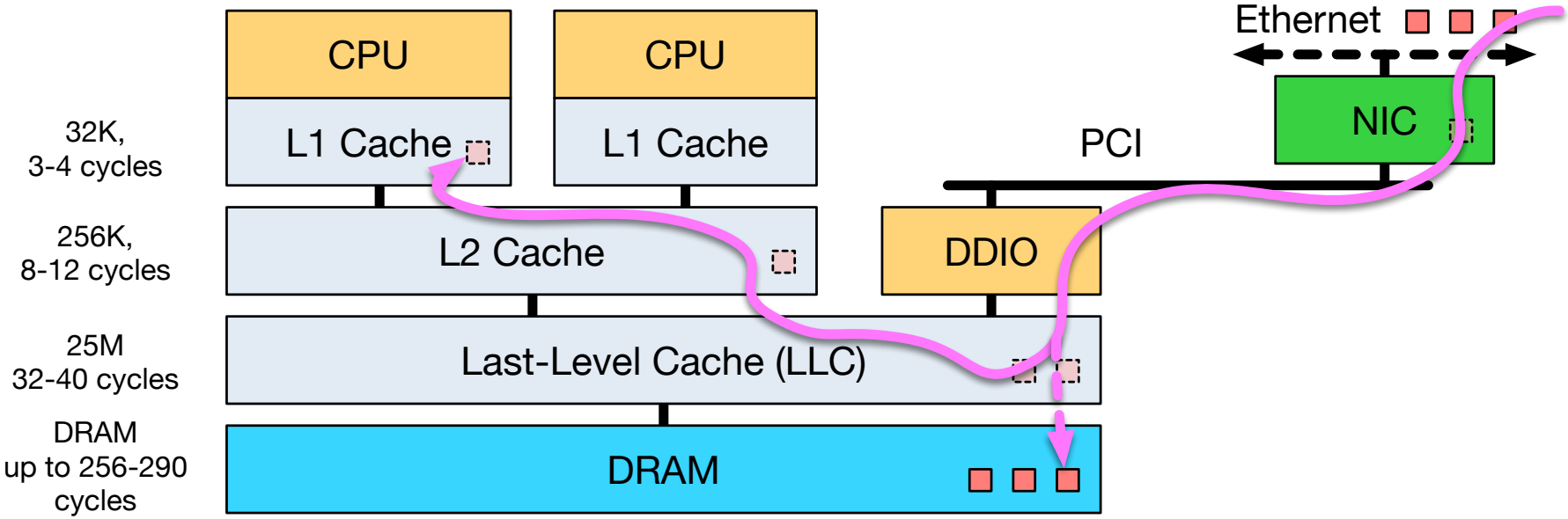
- Software model:
  - Flexible memory model integrates with VM for zero-copy
  - Network-stack virtualisation
  - Userspace networking via `netmap`

Memory flow in hardware



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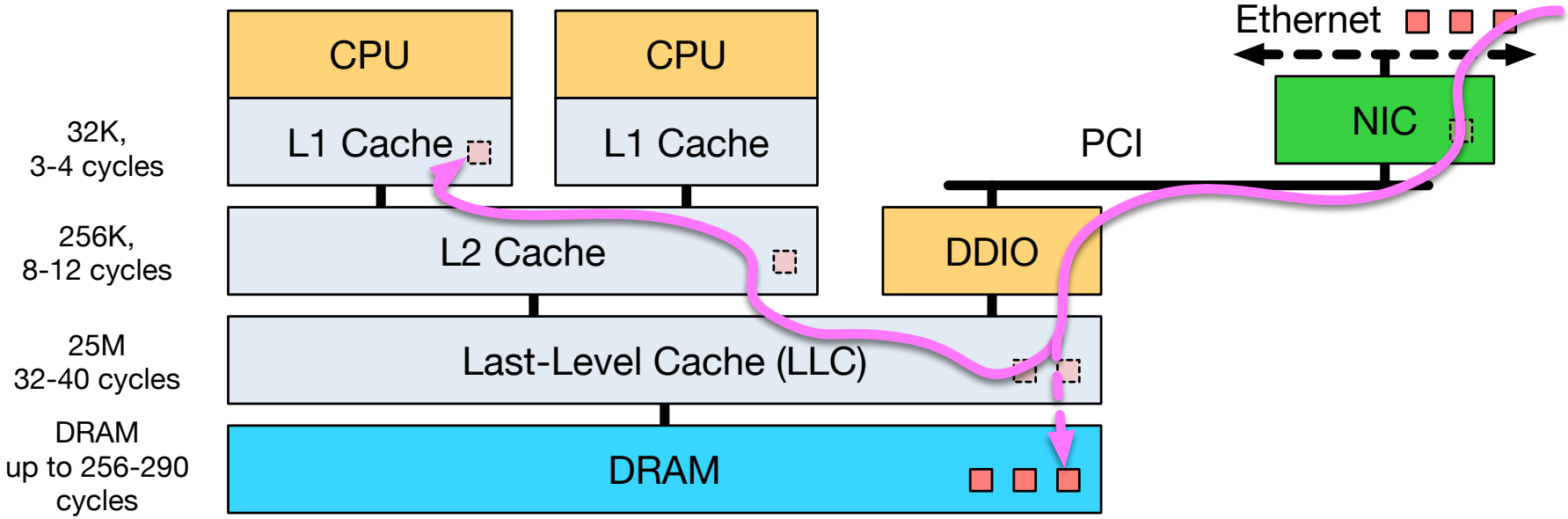

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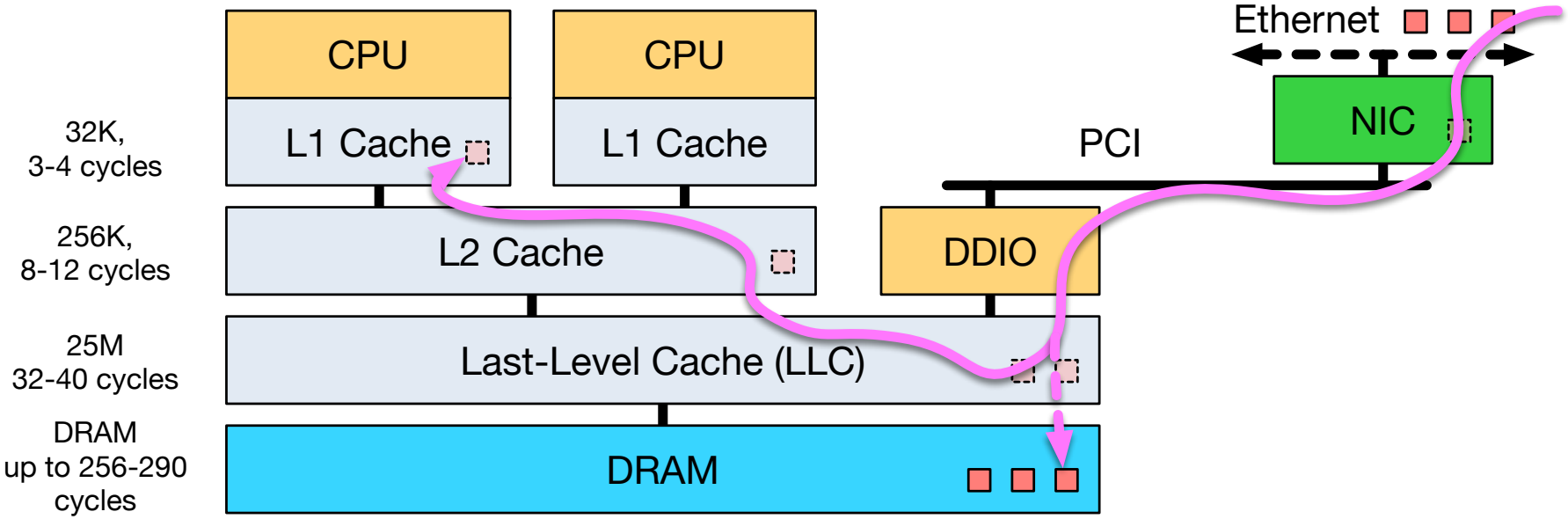

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- Historically, memory copying avoided due to CPU cost
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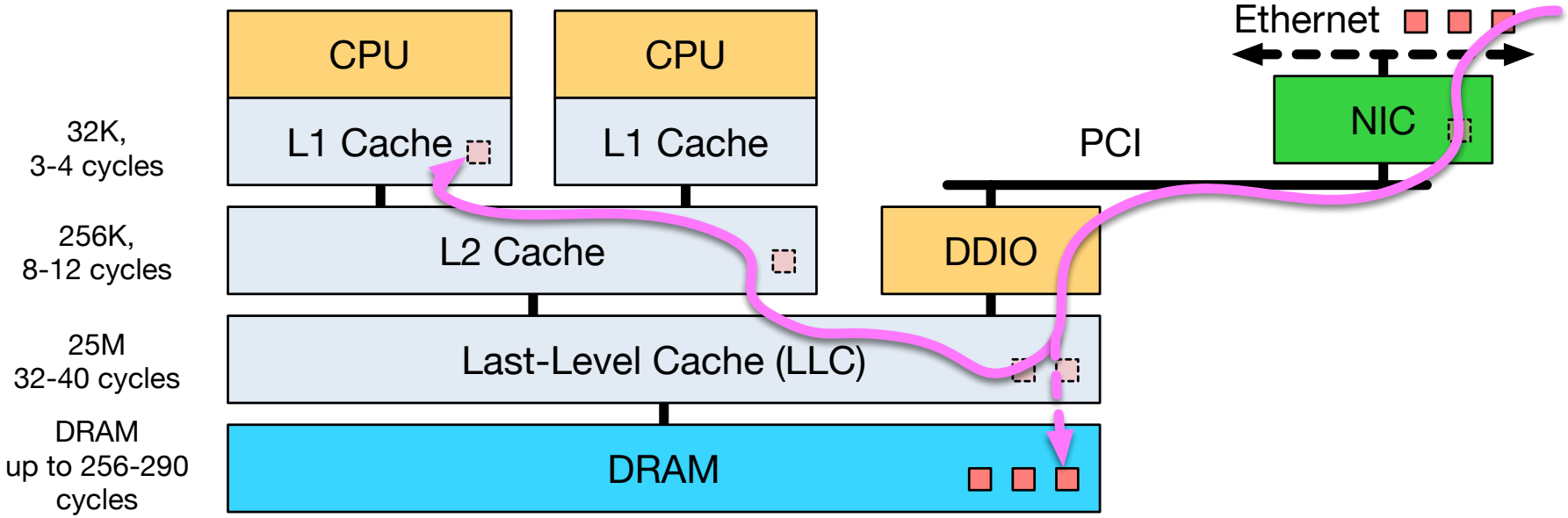

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- Historically, memory copying avoided due to CPU cost
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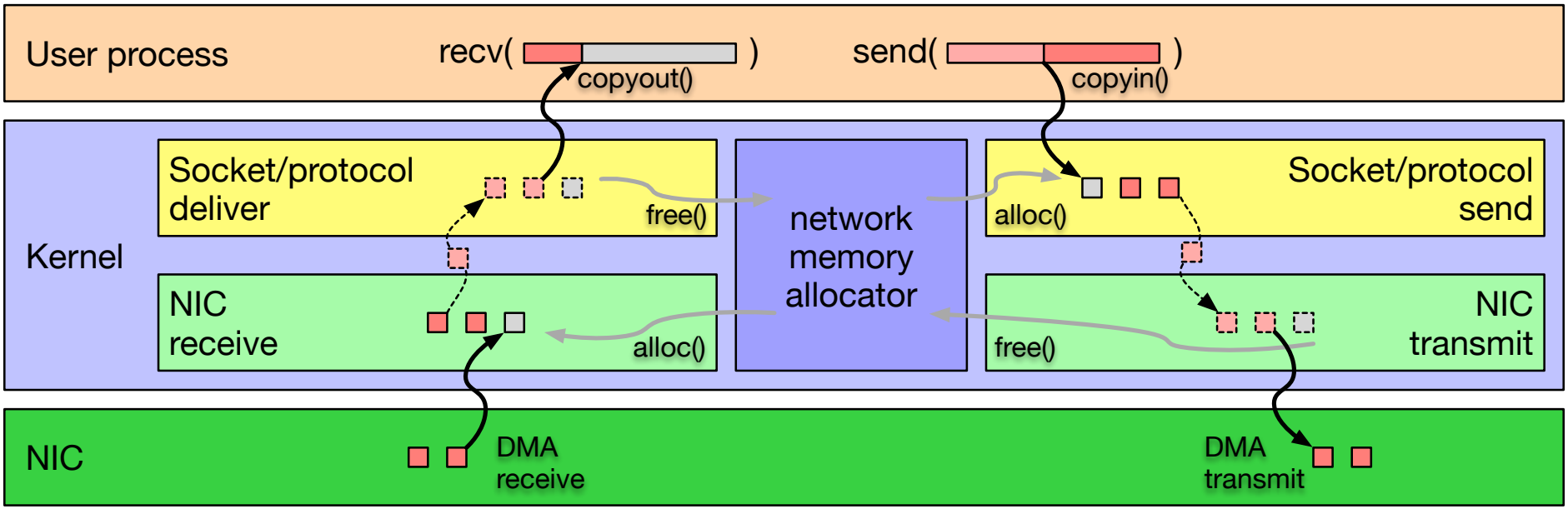
- Recent Intel CPUs push and pull DMA via the LLC (“DDIO”)
- NB: if we differentiate ‘send’ and ‘transmit’, is this a good idea?

Memory flow in software



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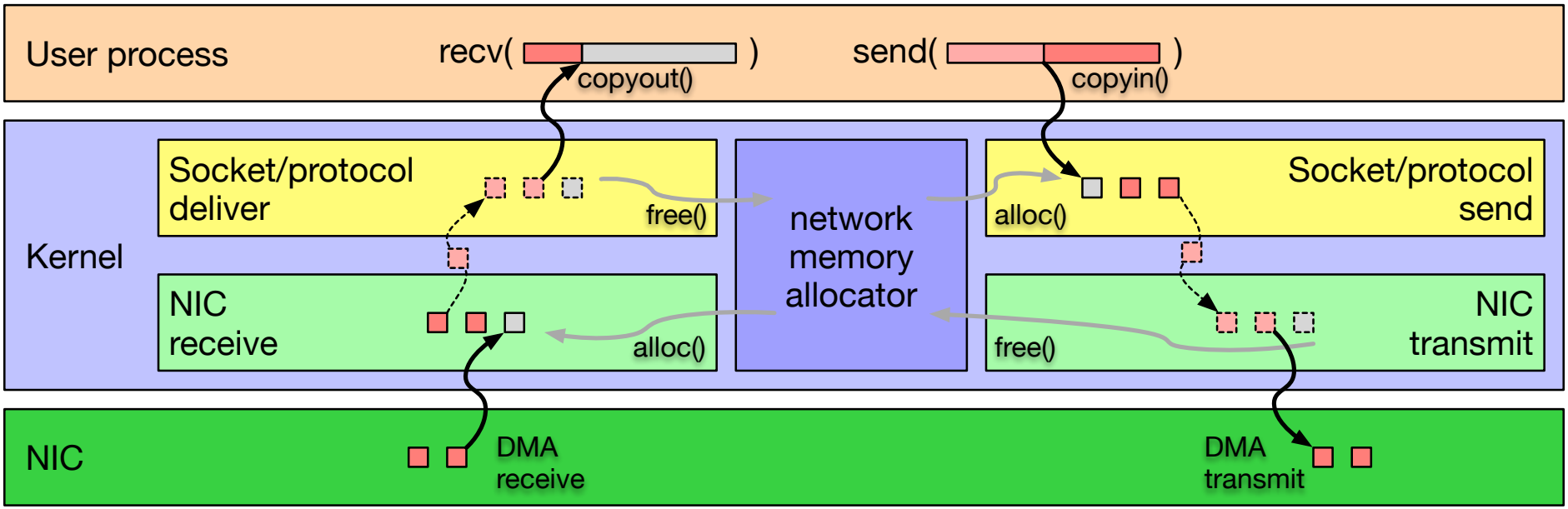

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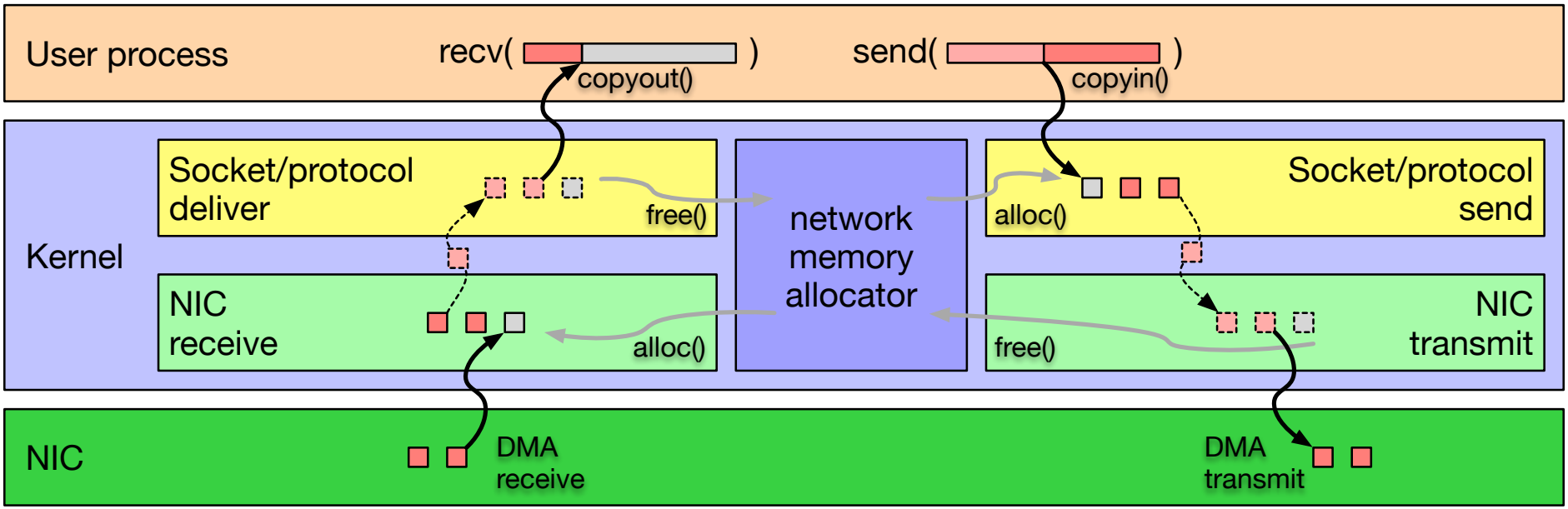

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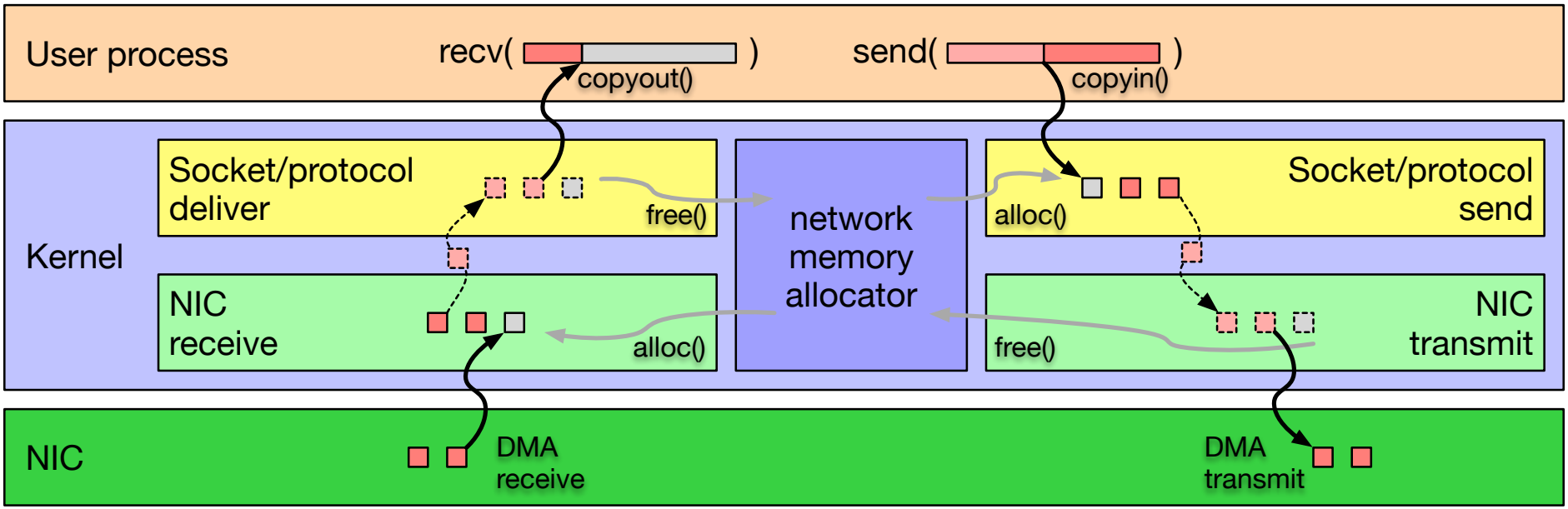

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- Network buffers cycle through the slab allocator
  - Receive: allocate in NIC driver, free in socket layer
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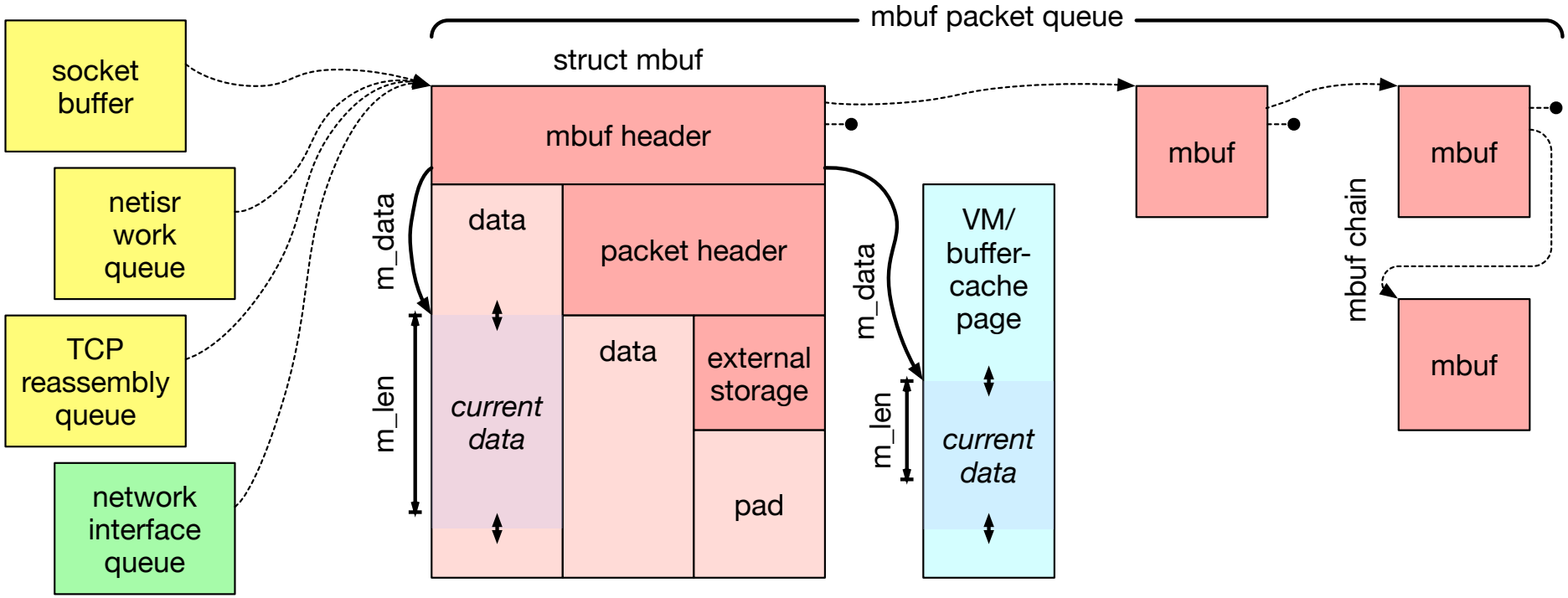
- DMA performs second copy; can affect cache/memory bandwidth
  - NB: what if packet-buffer working set is larger than the cache?

The `mbuf` abstraction



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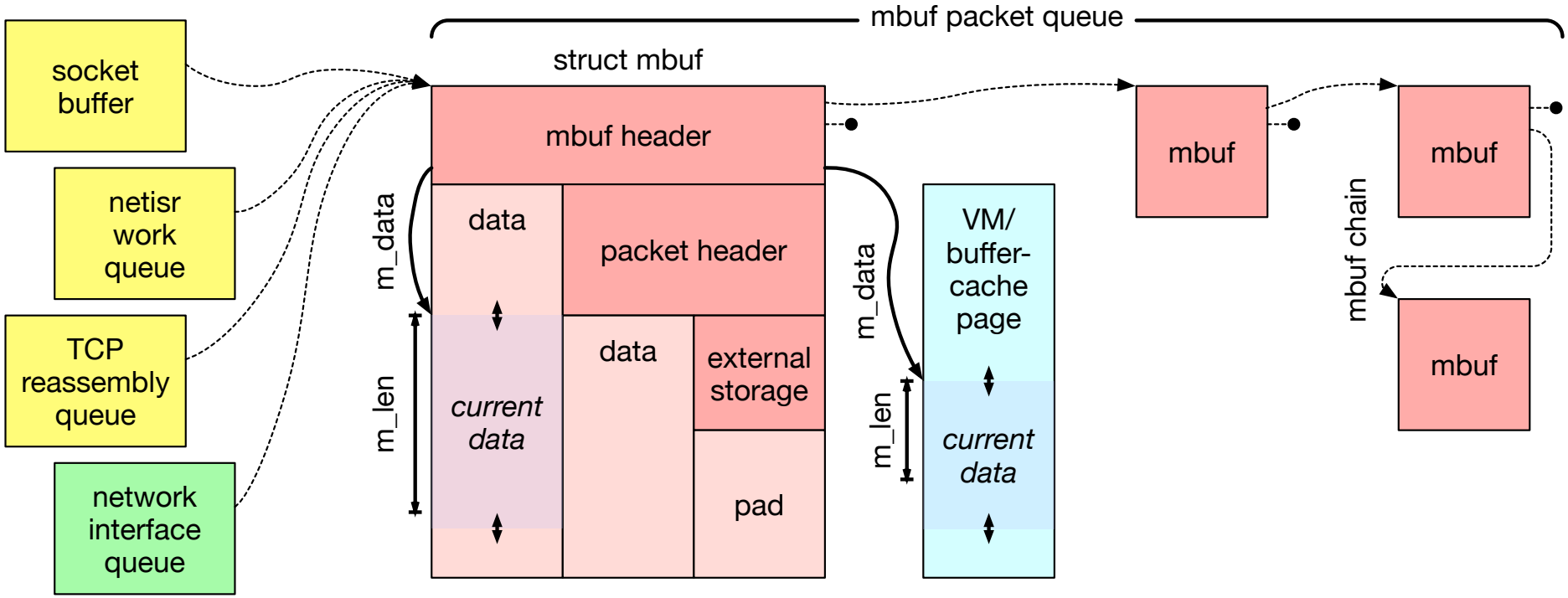

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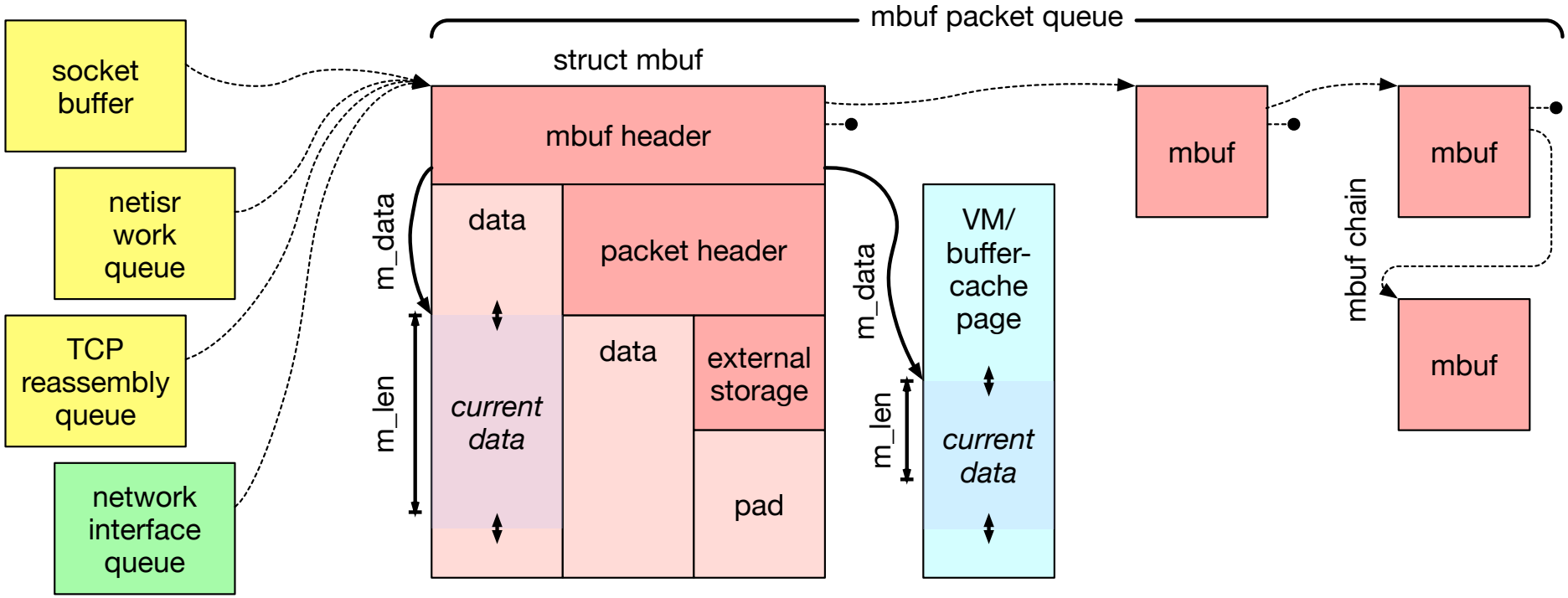

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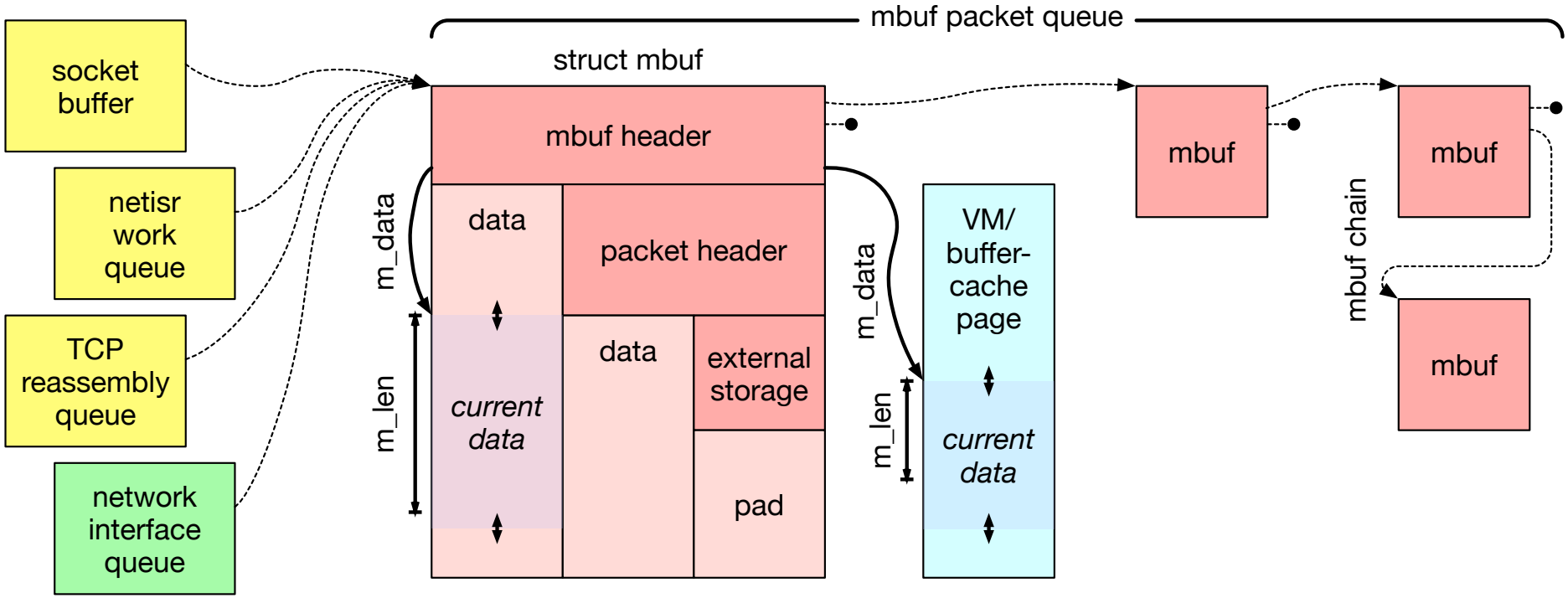

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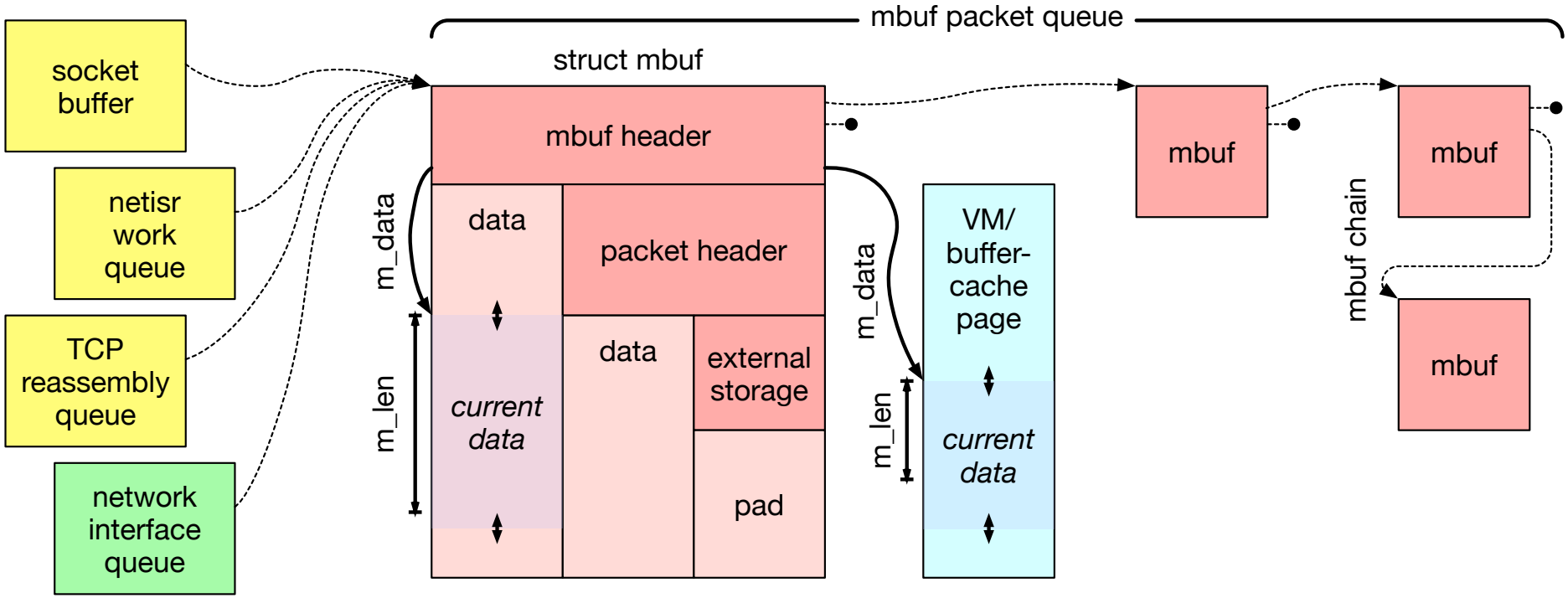

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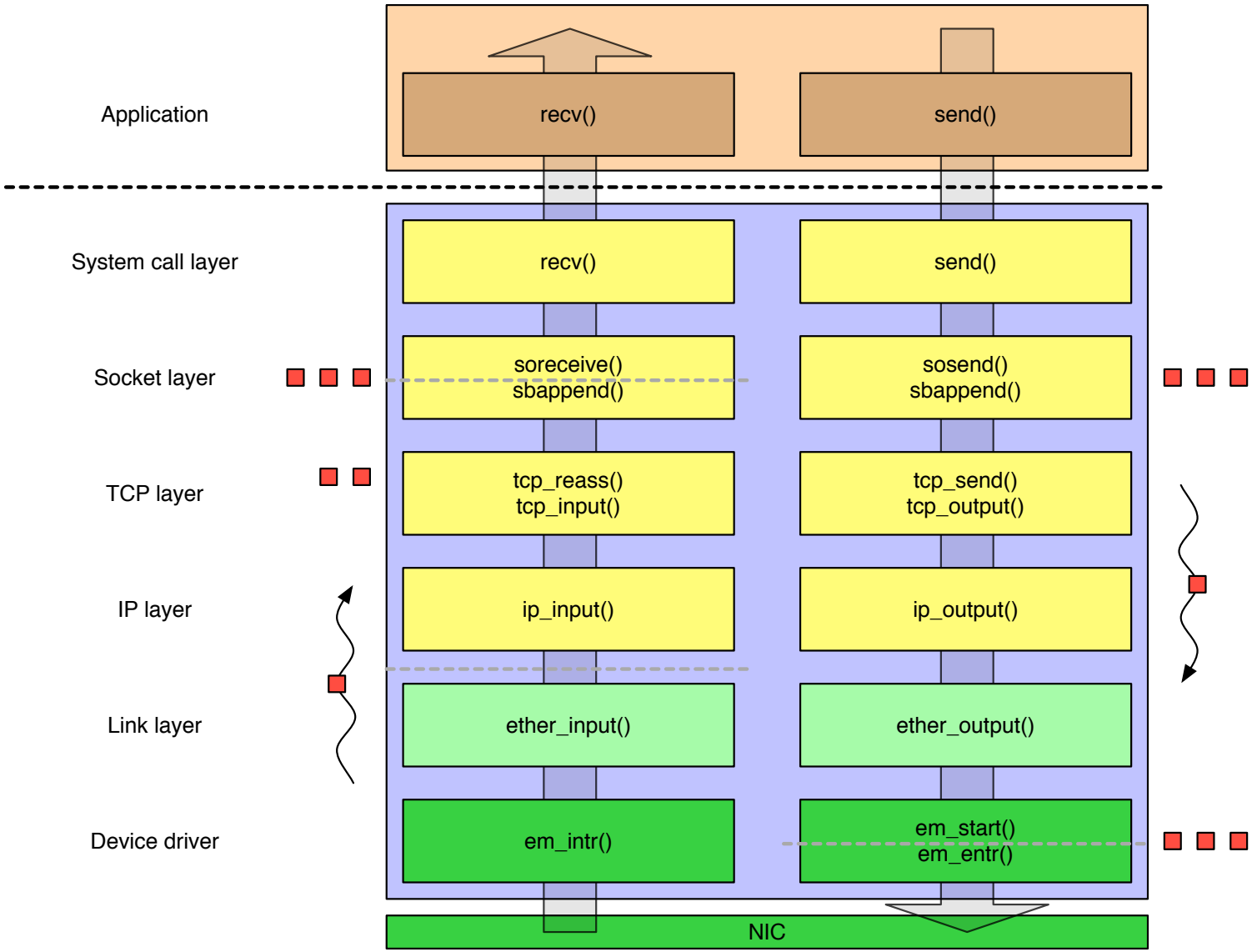
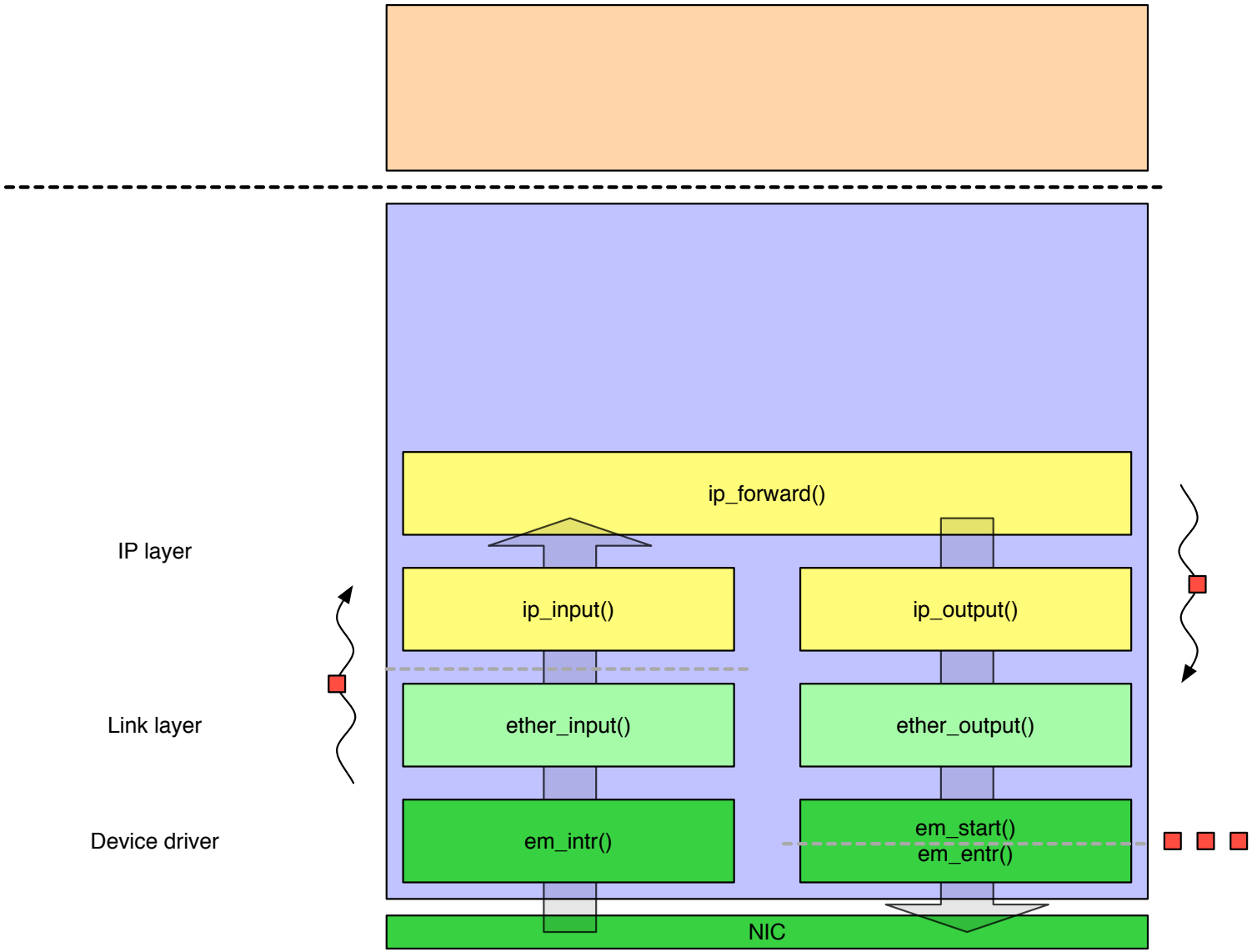
- Unit of **work allocation and distribution** throughout the stack
- Similar structures in other OSes – e.g., `skbuff` in Linux

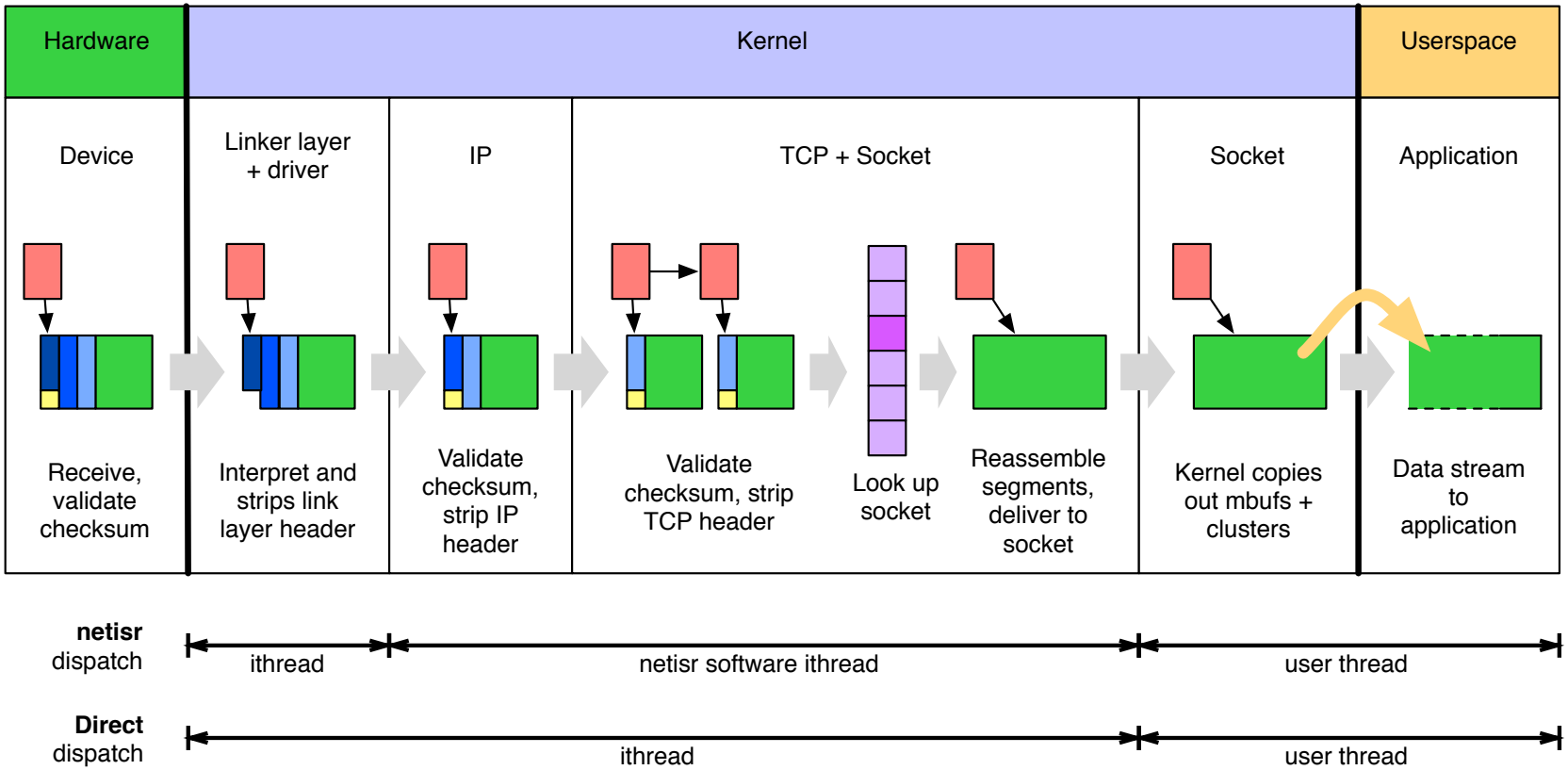
Local send/receive paths in the network stack



Forwarding path in the network stack



Work dispatch: input path



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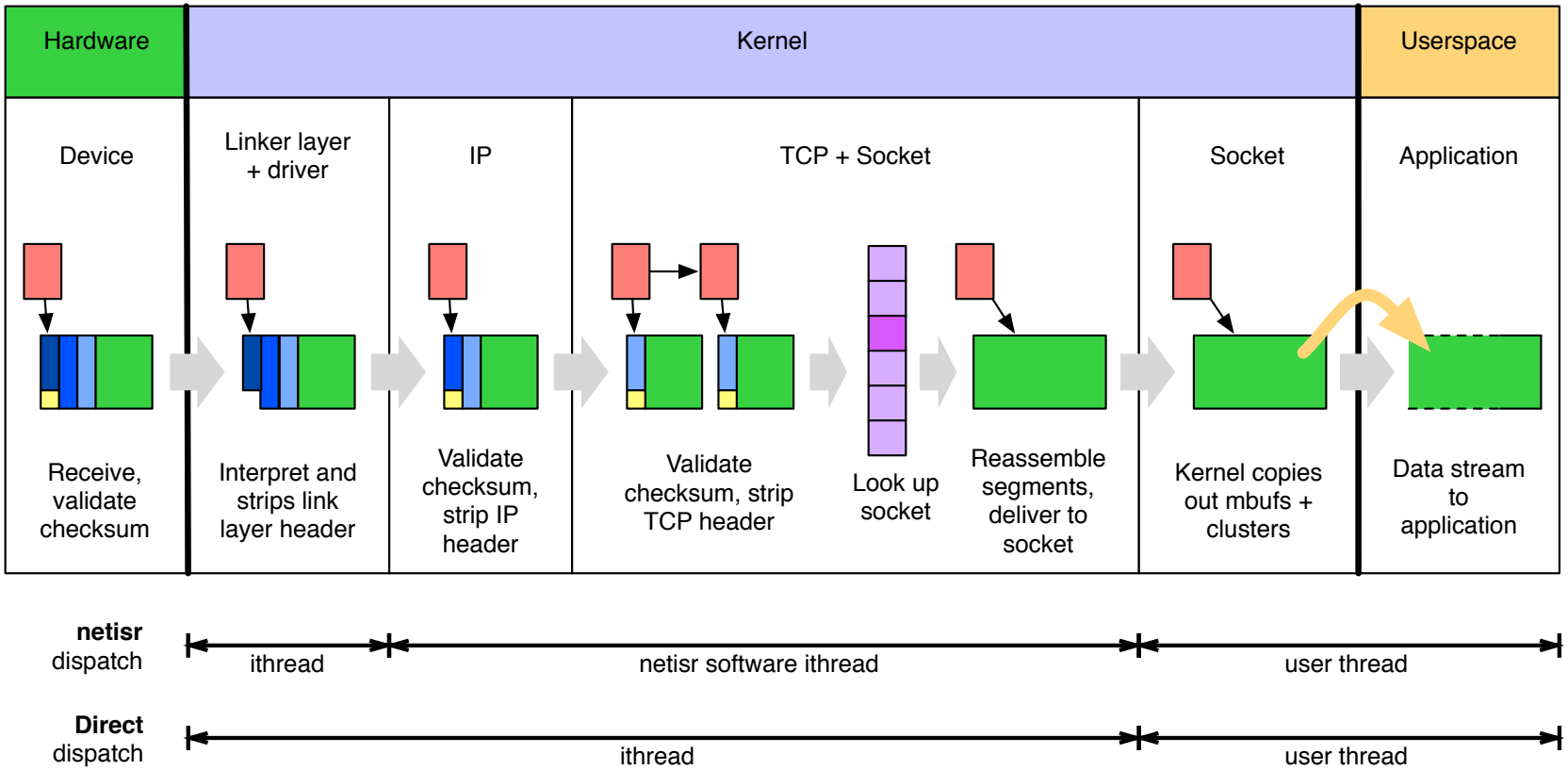

- Deferred dispatch - *ithread -> netisr thread -> user thread*

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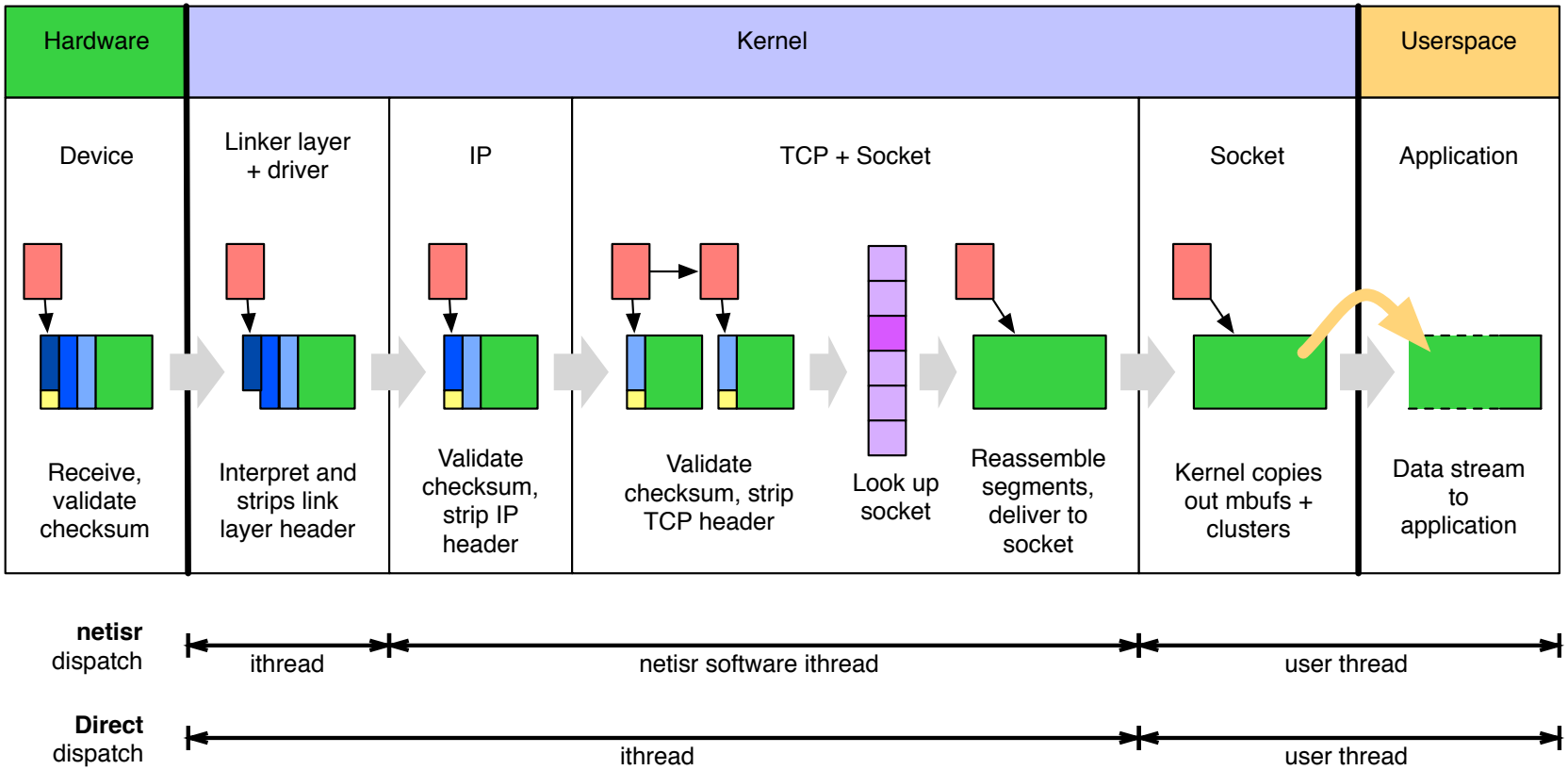
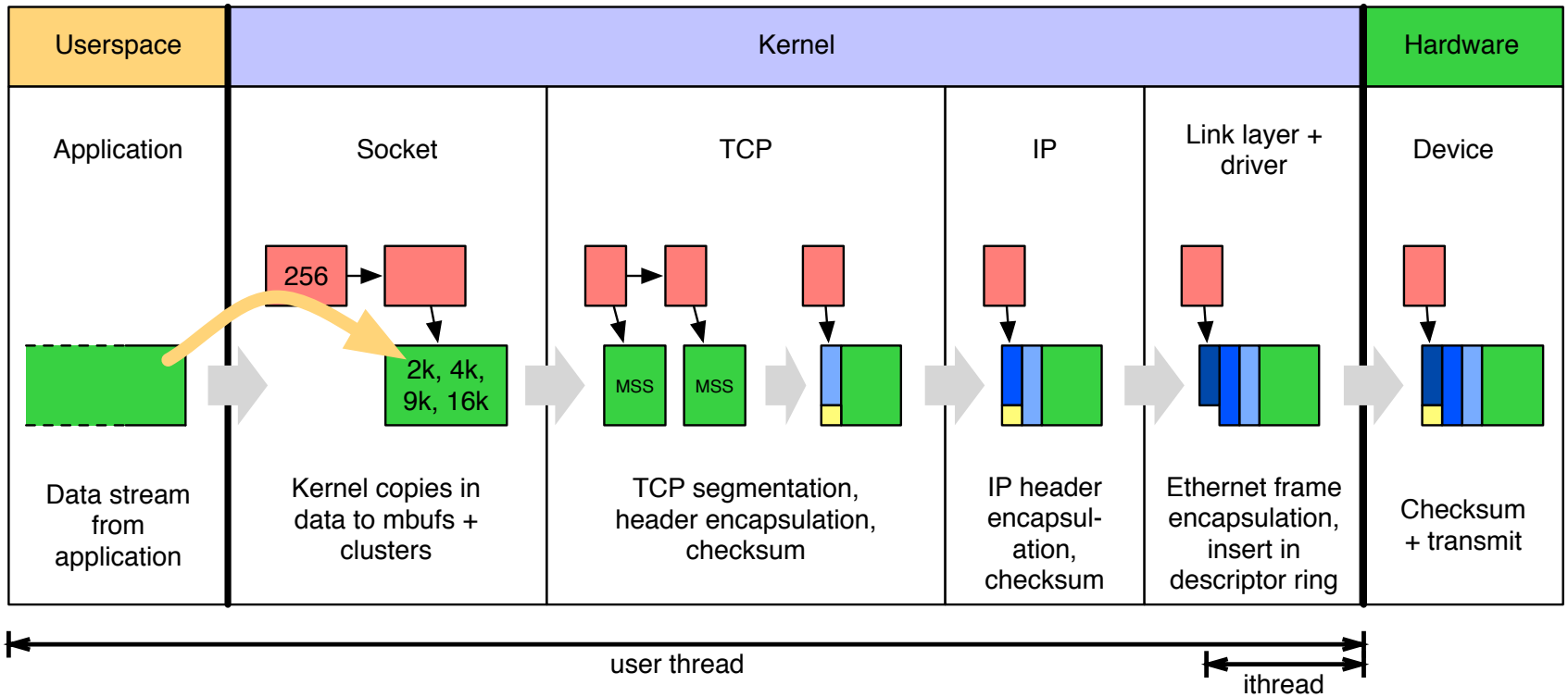


- Deferred dispatch - *ithread -> netisr thread -> user thread*
- Now: direct dispatch - *ithread -> user thread*
  - Pros: reduced latency, better cache locality, drop overload early
  - Cons: reduced parallelism and work placement opportunities

Work dispatch: output path



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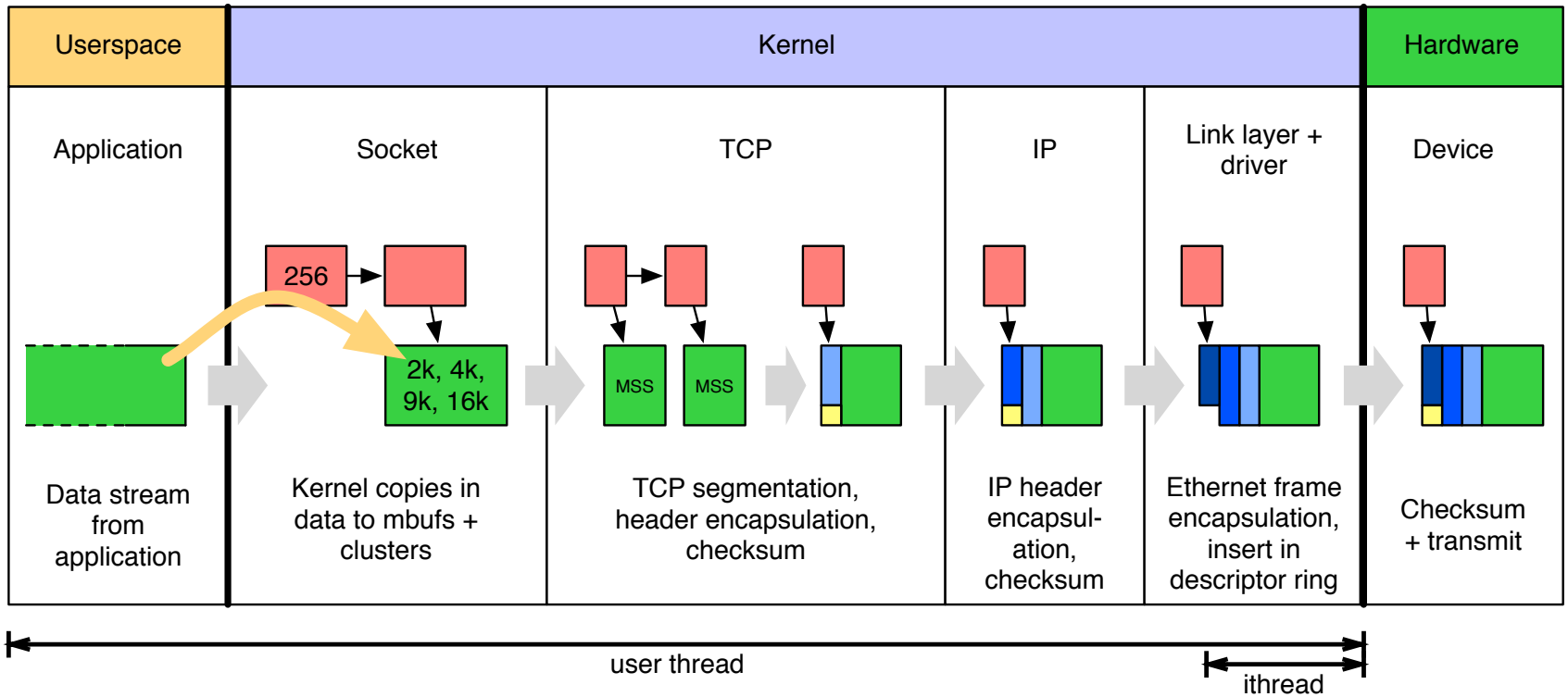

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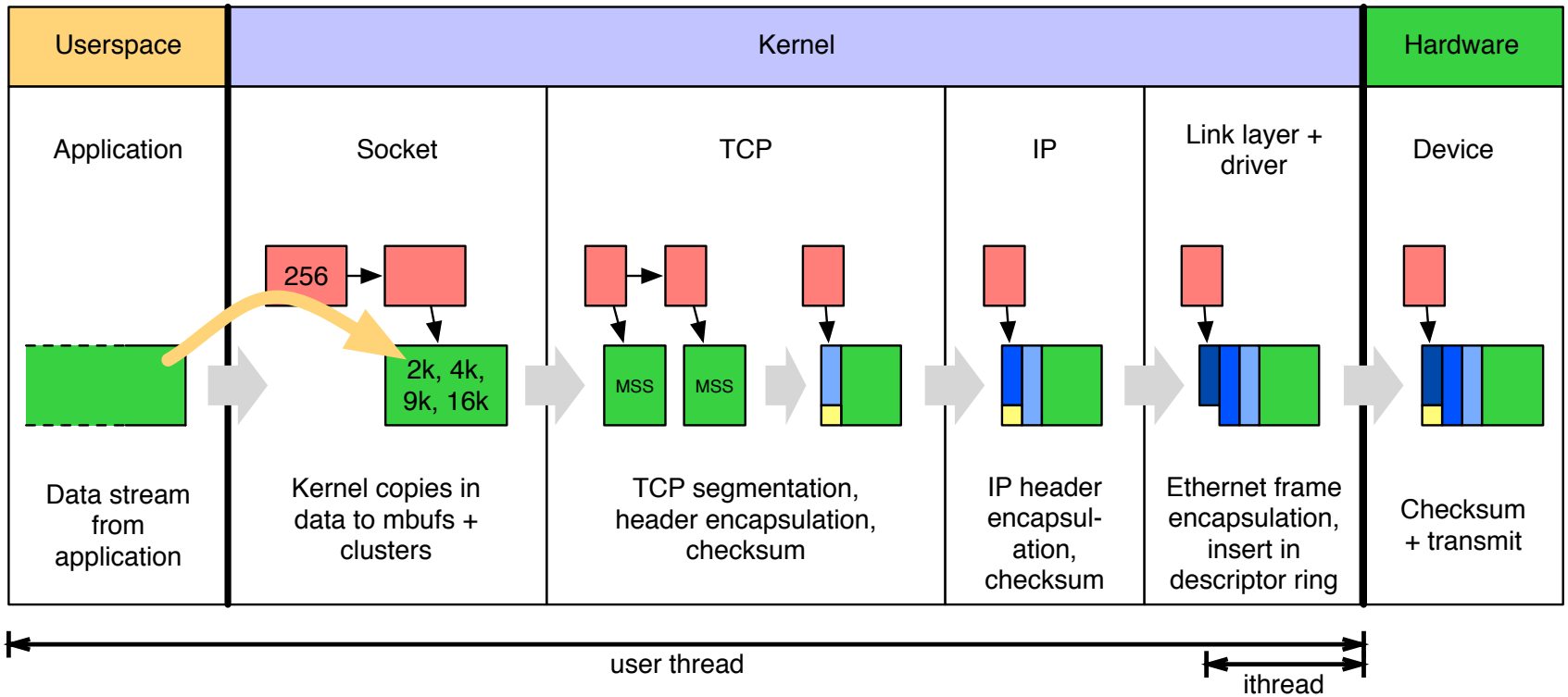

- Fewer deferred dispatch opportunities implemented
- Gradual shift of work from software to hardware
  - Checksum calculation, segmentation, ...

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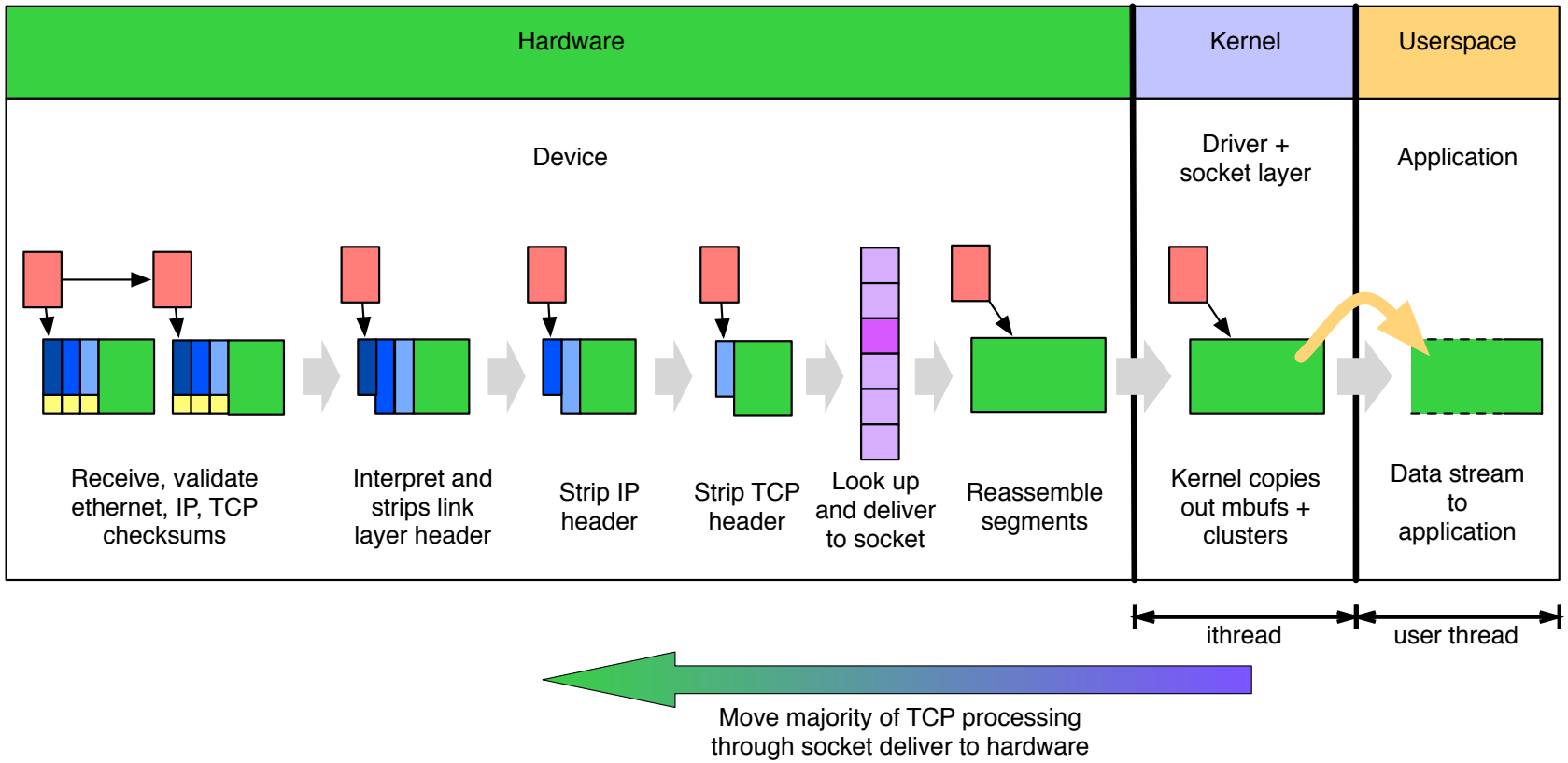

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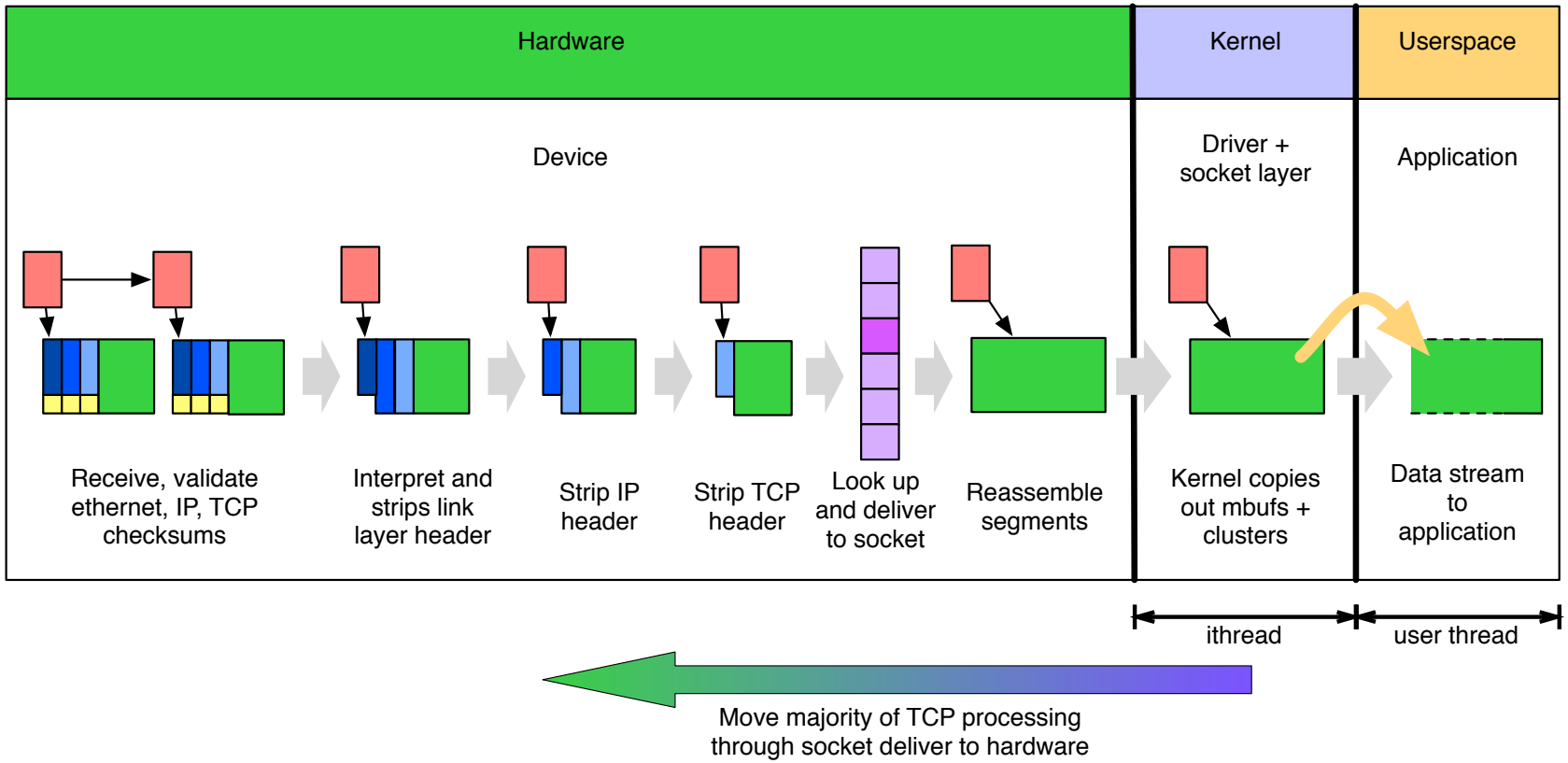

- Full TCP offload
  - Kernel provides socket buffers and resource allocation
  - Remainder, including state, retransmits, reassembly, etc, in NIC

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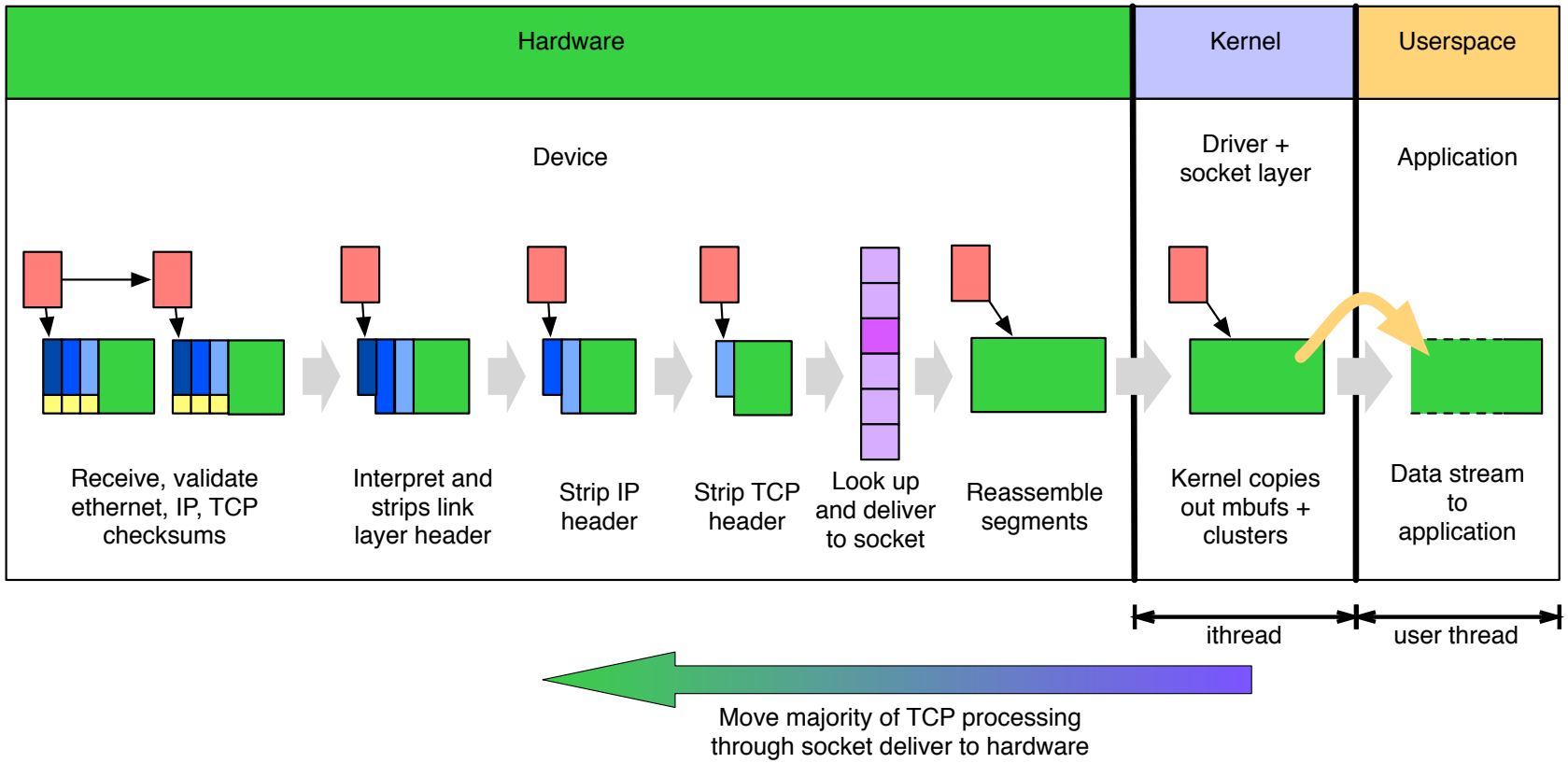
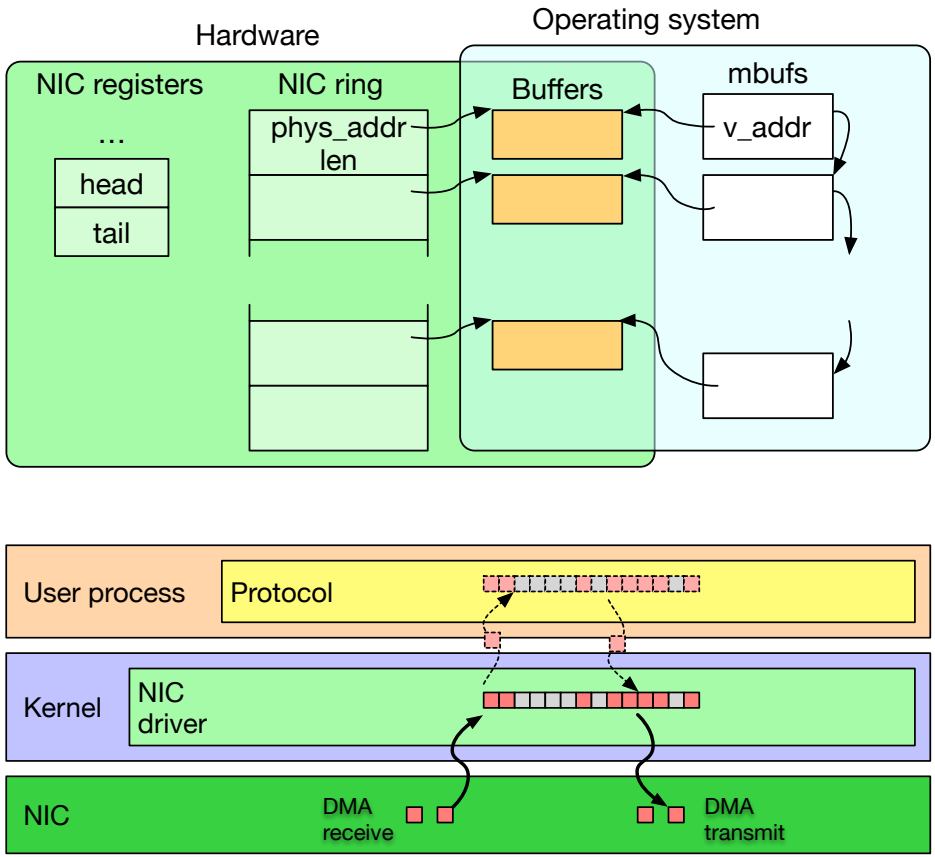


- Full TCP offload
  - Kernel provides socket buffers and resource allocation
  - Remainder, including state, retransmits, reassembly, etc, in NIC
- But: Two network stacks? Less flexible/updateable structure?
- Better with an explicit HW/SW architecture – e.g., Microsoft Chimney?

netmap: a novel framework for fast packet I/O

Luigi Rizzo, USENIX ATC 2012 (best paper).



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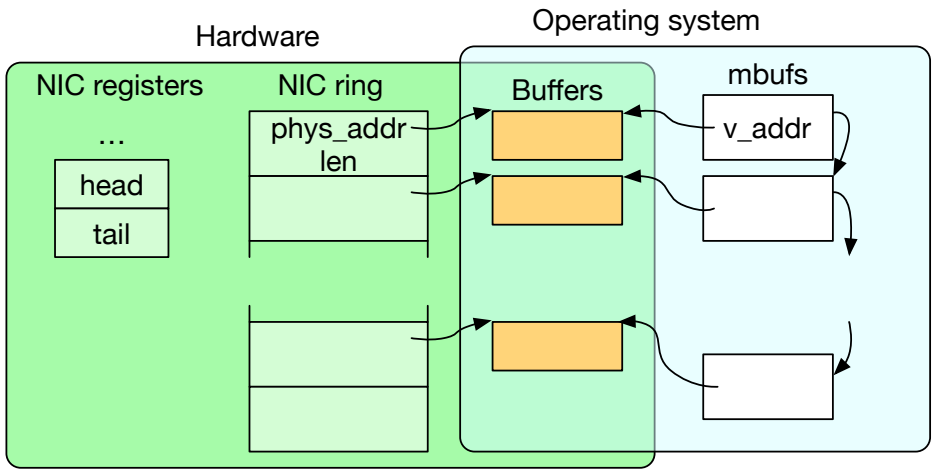

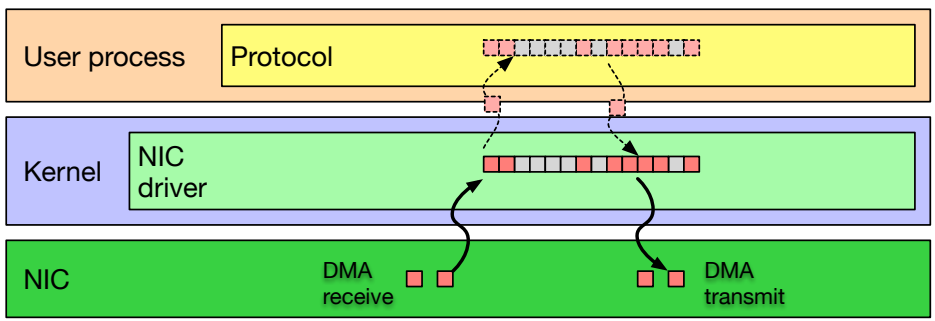

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- Zero copy to/from app.

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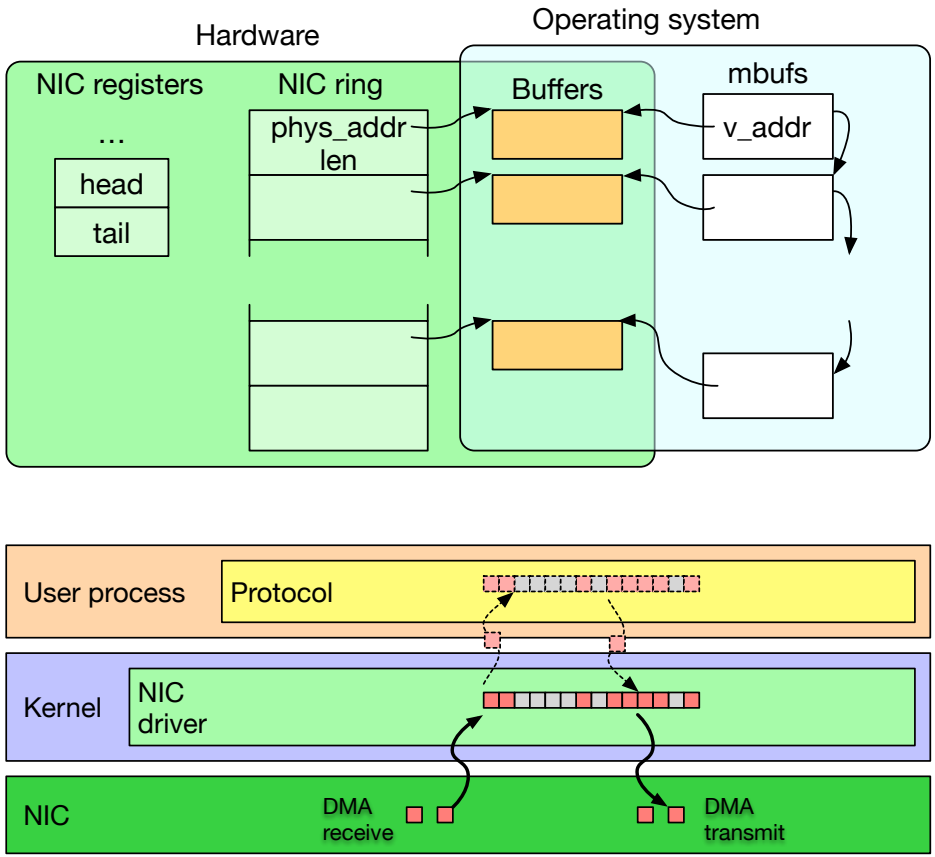

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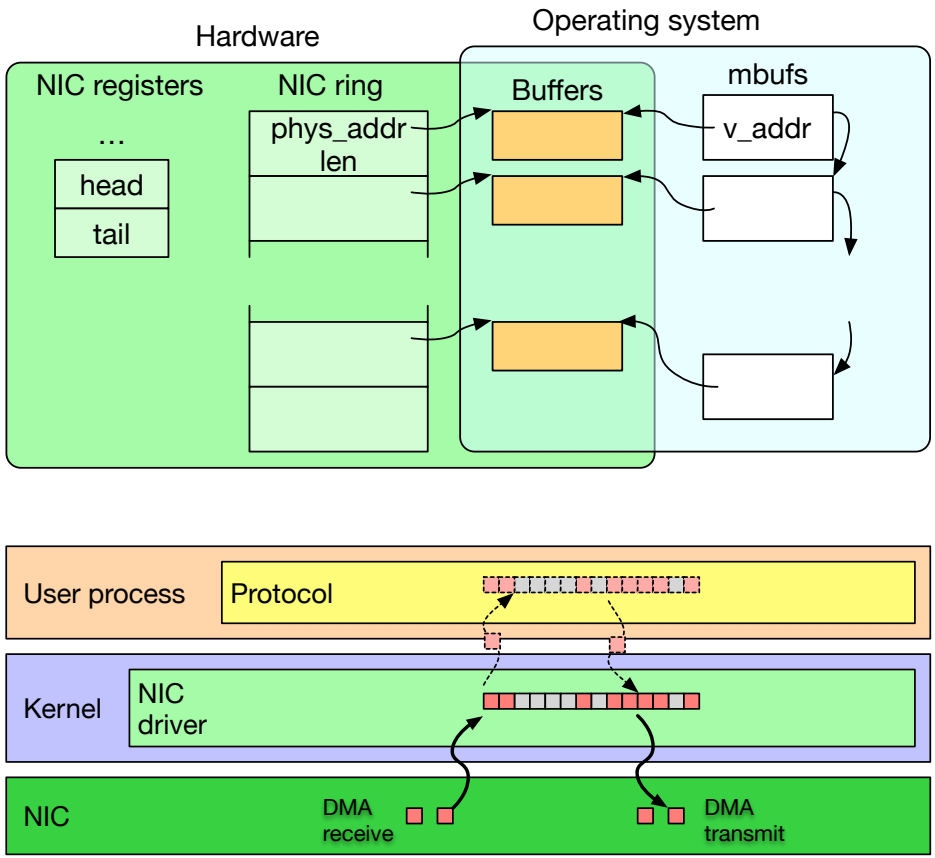

- Map NIC buffers directly into user process memory
- Zero copy to/from app.
- System calls initiate DMA, block for NIC events
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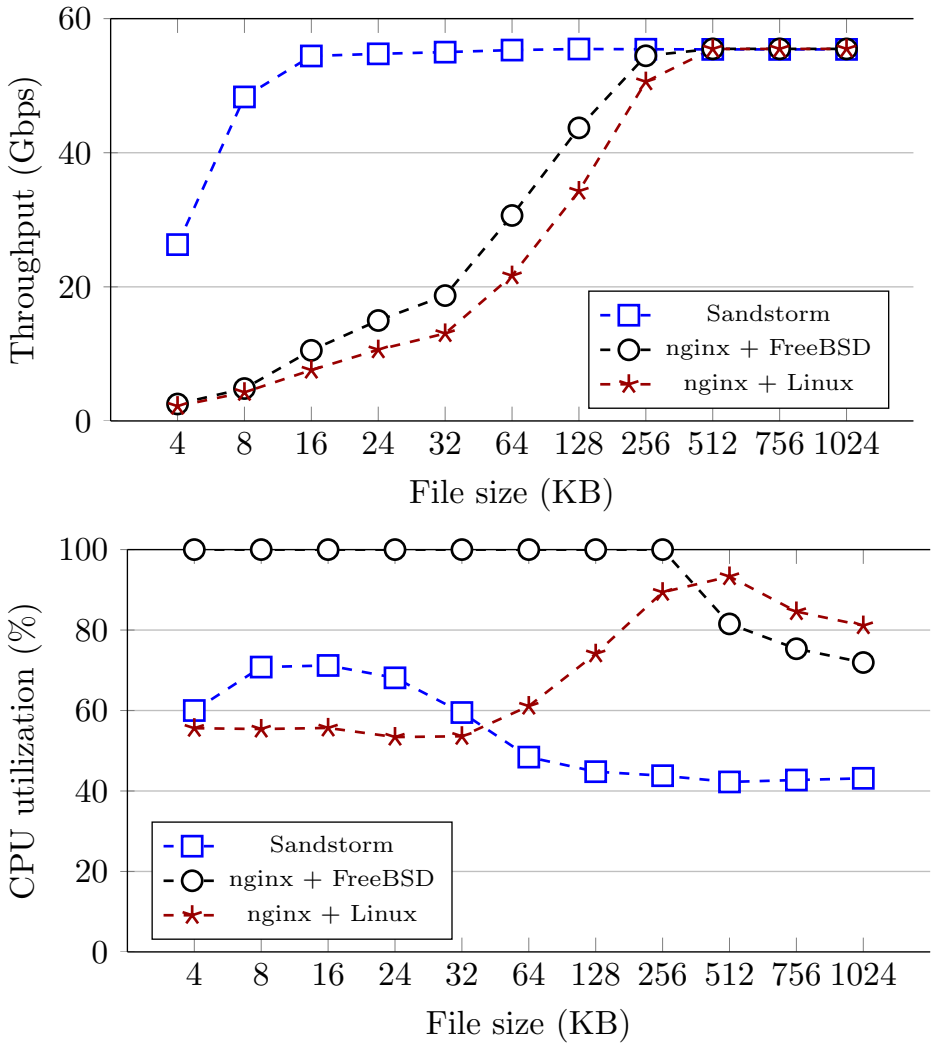
- Ships in FreeBSD, patch available for Linux
- Userspace network stack can be **specialized** to task (e.g., packet forwarding)

Network Stack Specialization for Performance

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



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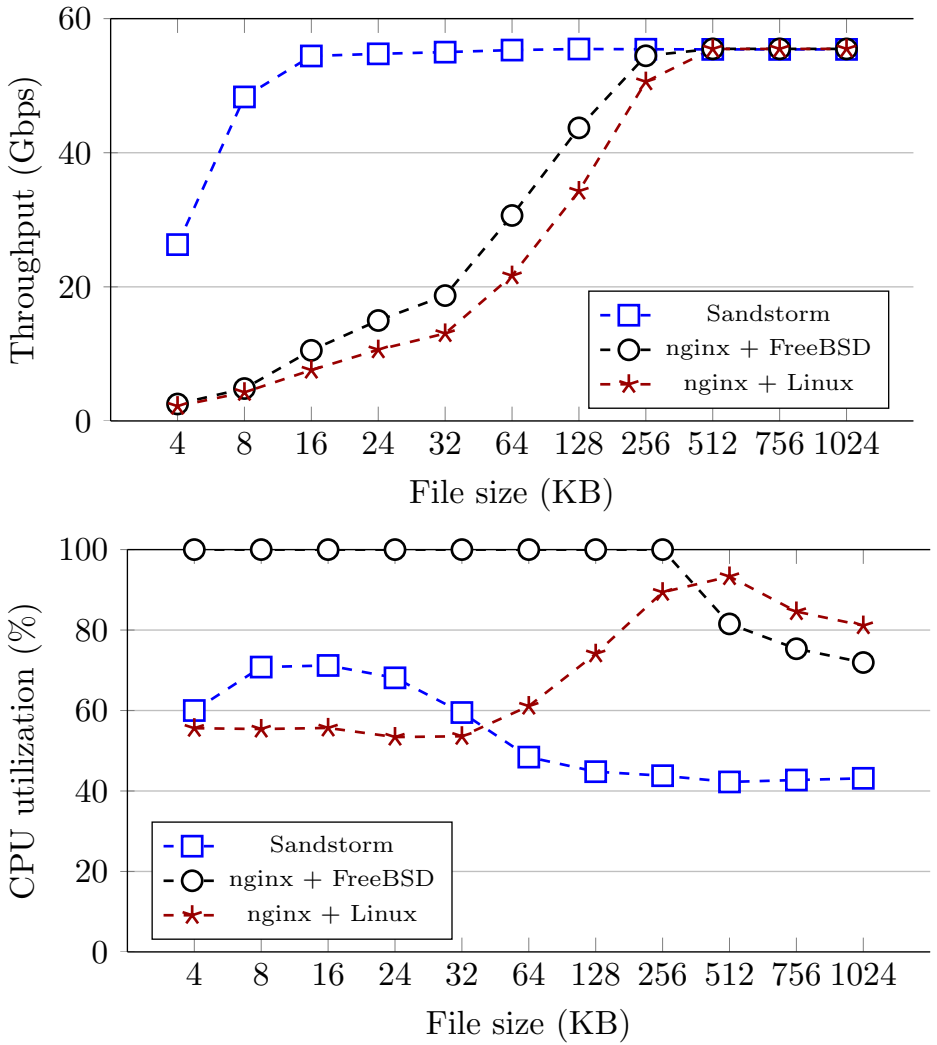

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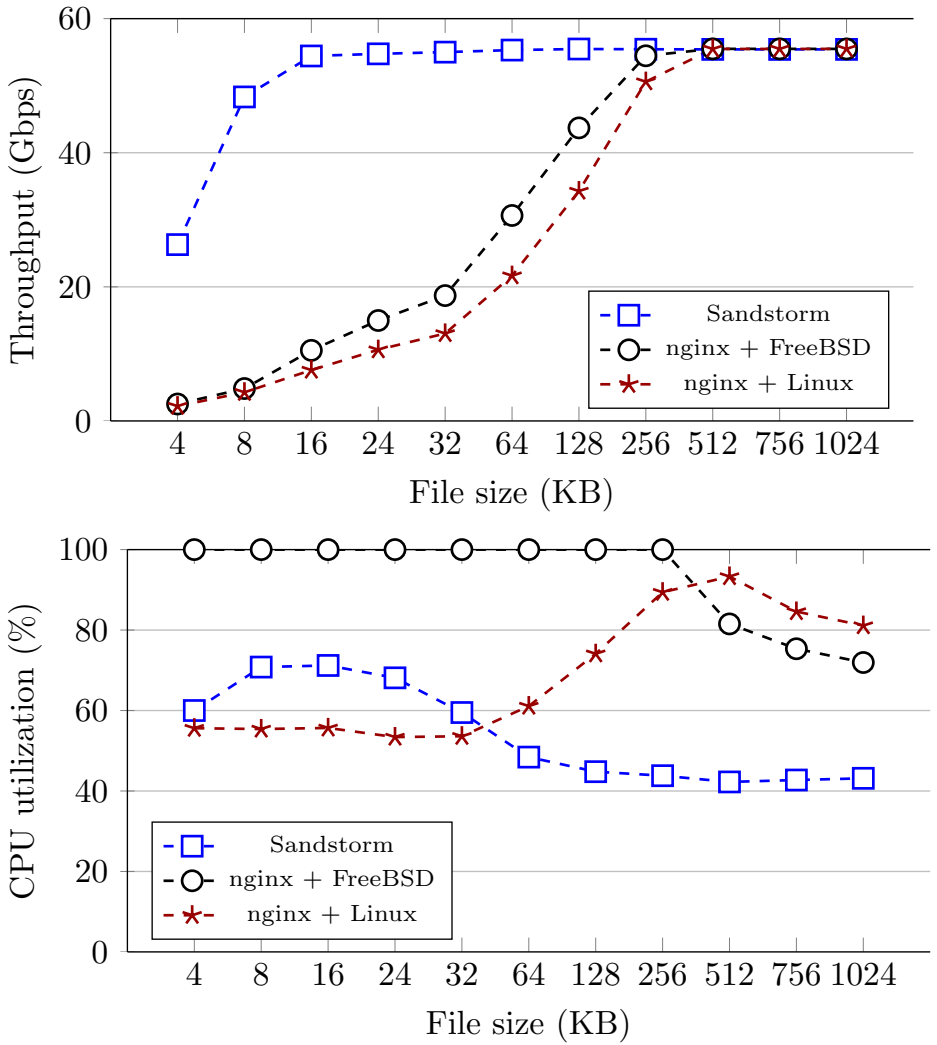

- 30 years since network-stack design developed
- Massive changes in architecture, micro-architecture, memory, buses, NICs
  - Optimising compilers
  - Cache-centered CPUs
  - Multiprocessing, NUMA
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  - 10 Gigabit/s Ethernet

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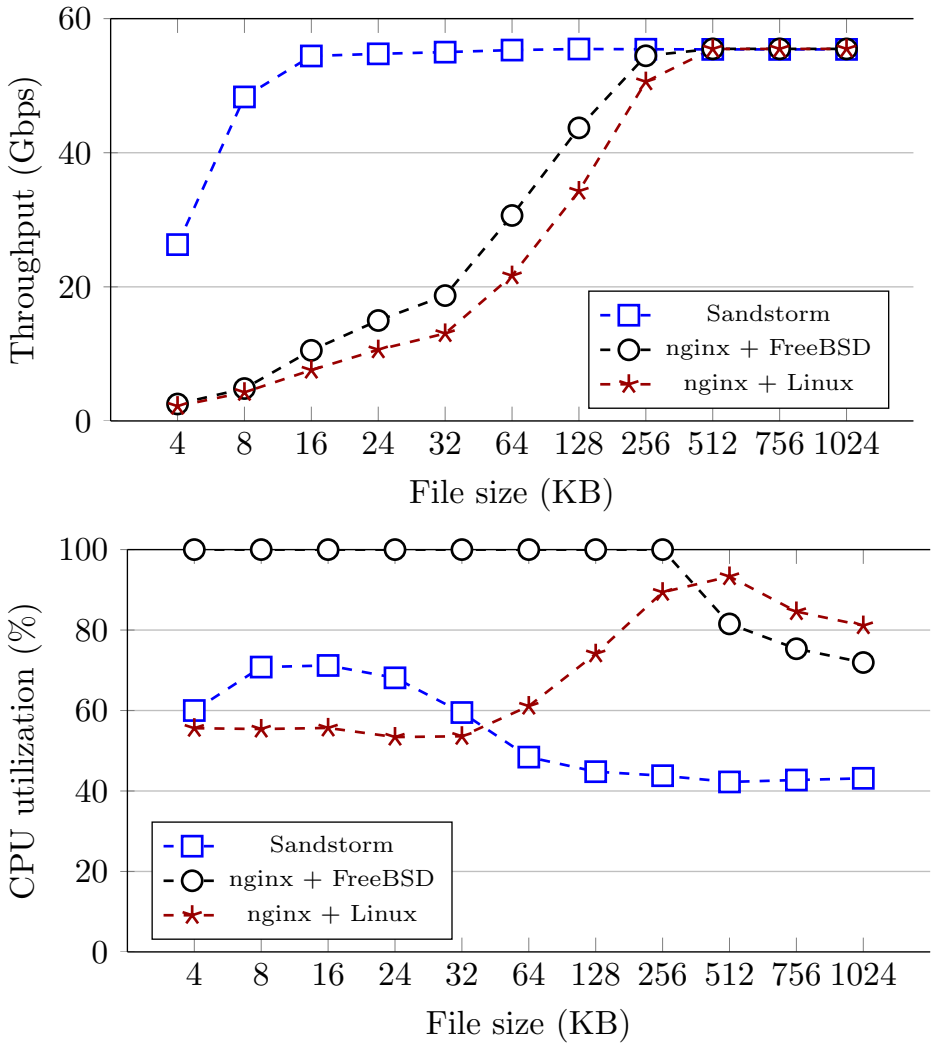

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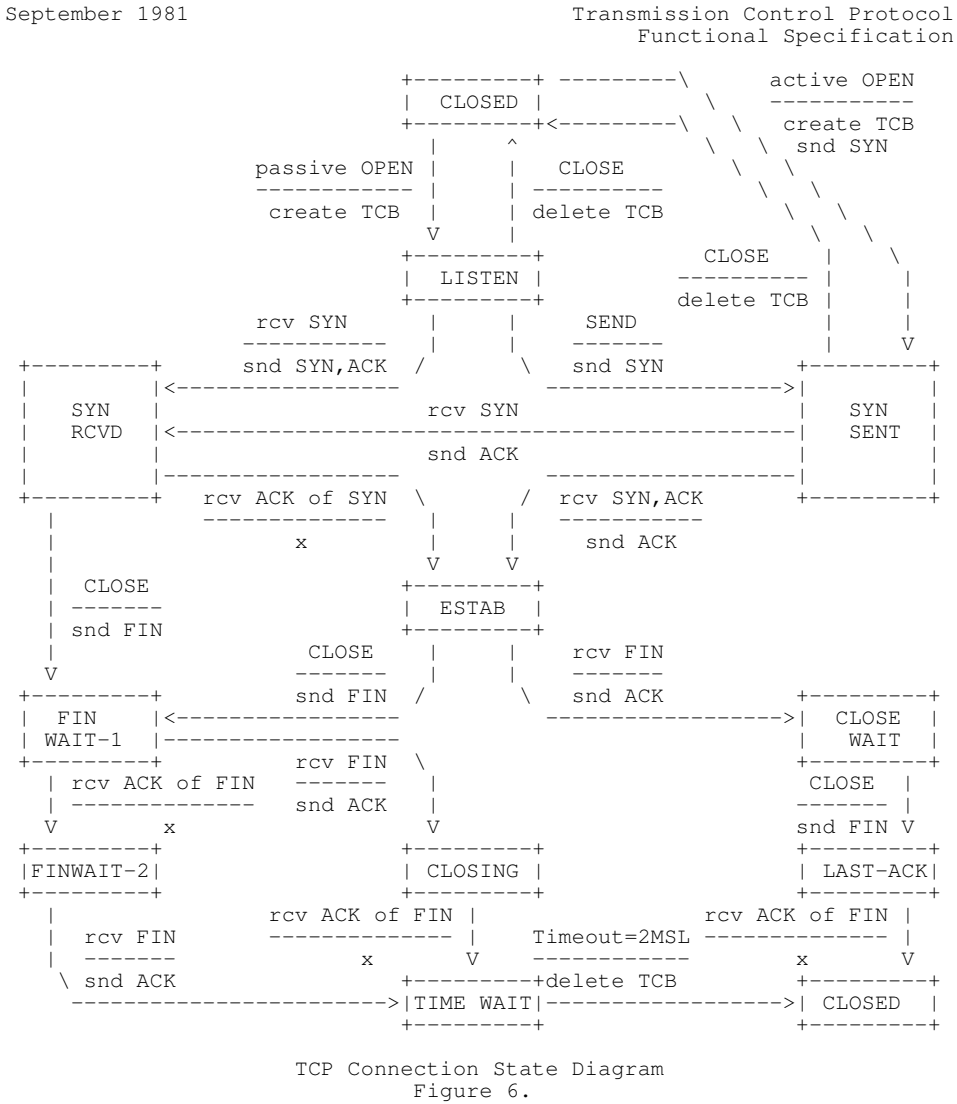
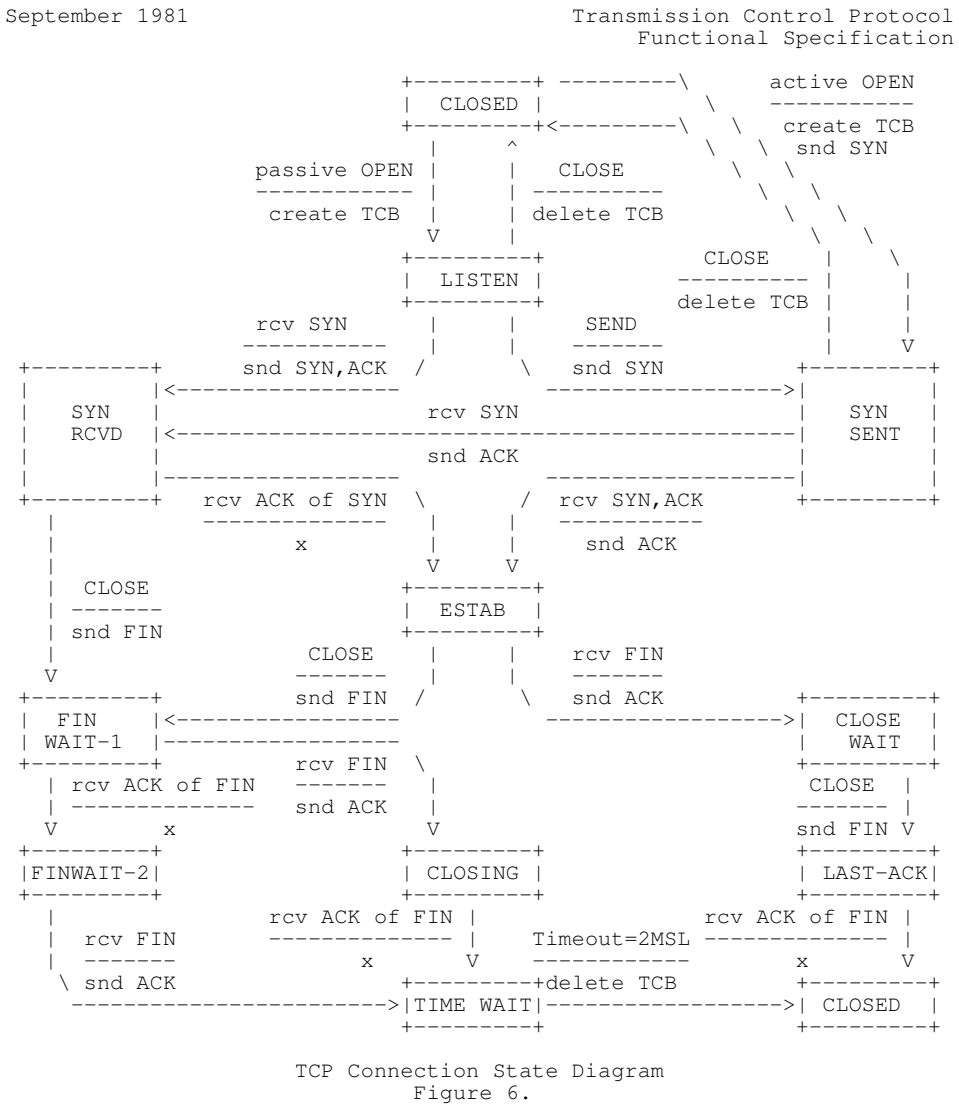
- Revisit fundamentals through clean-slate stack

Next time: Socket buffers and TCP



TCP Connection State Diagram
Figure 6.

Next time: Socket buffers and TCP



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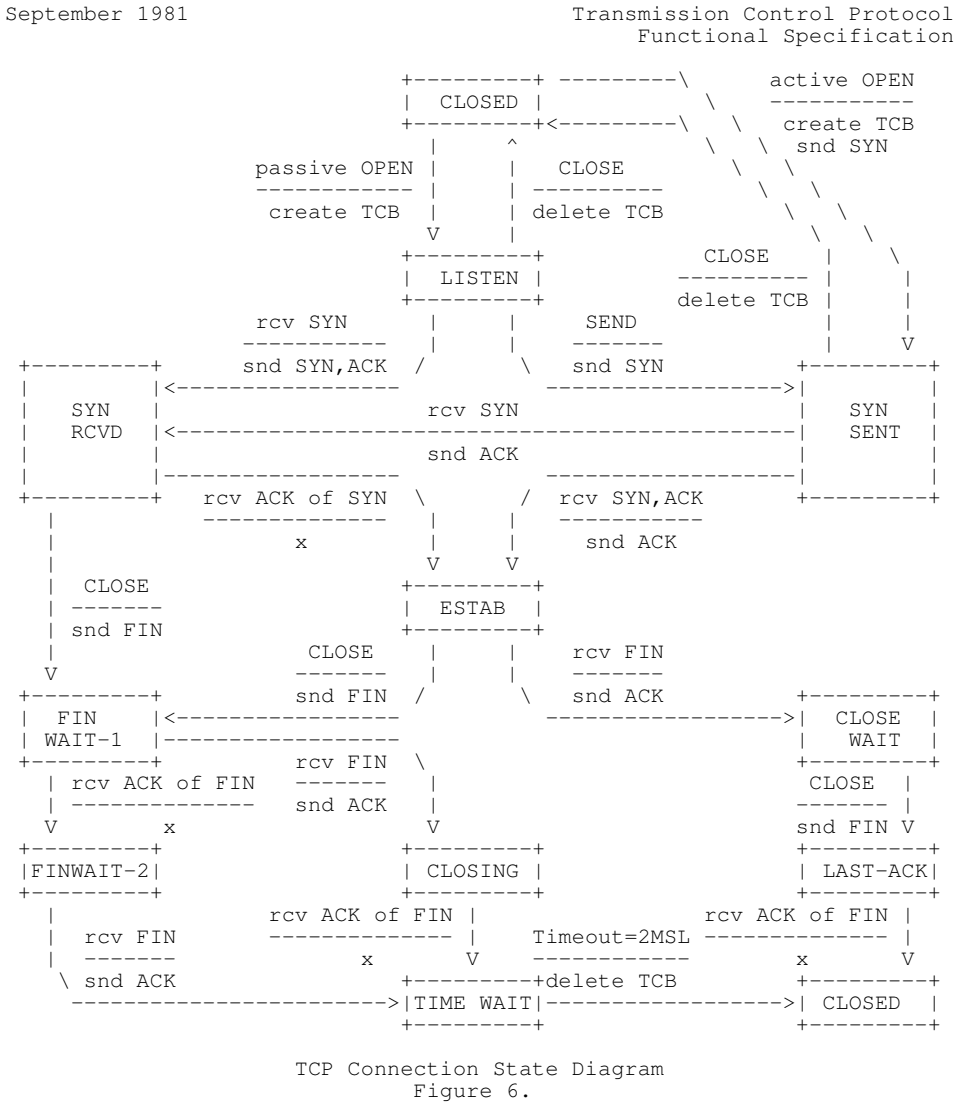

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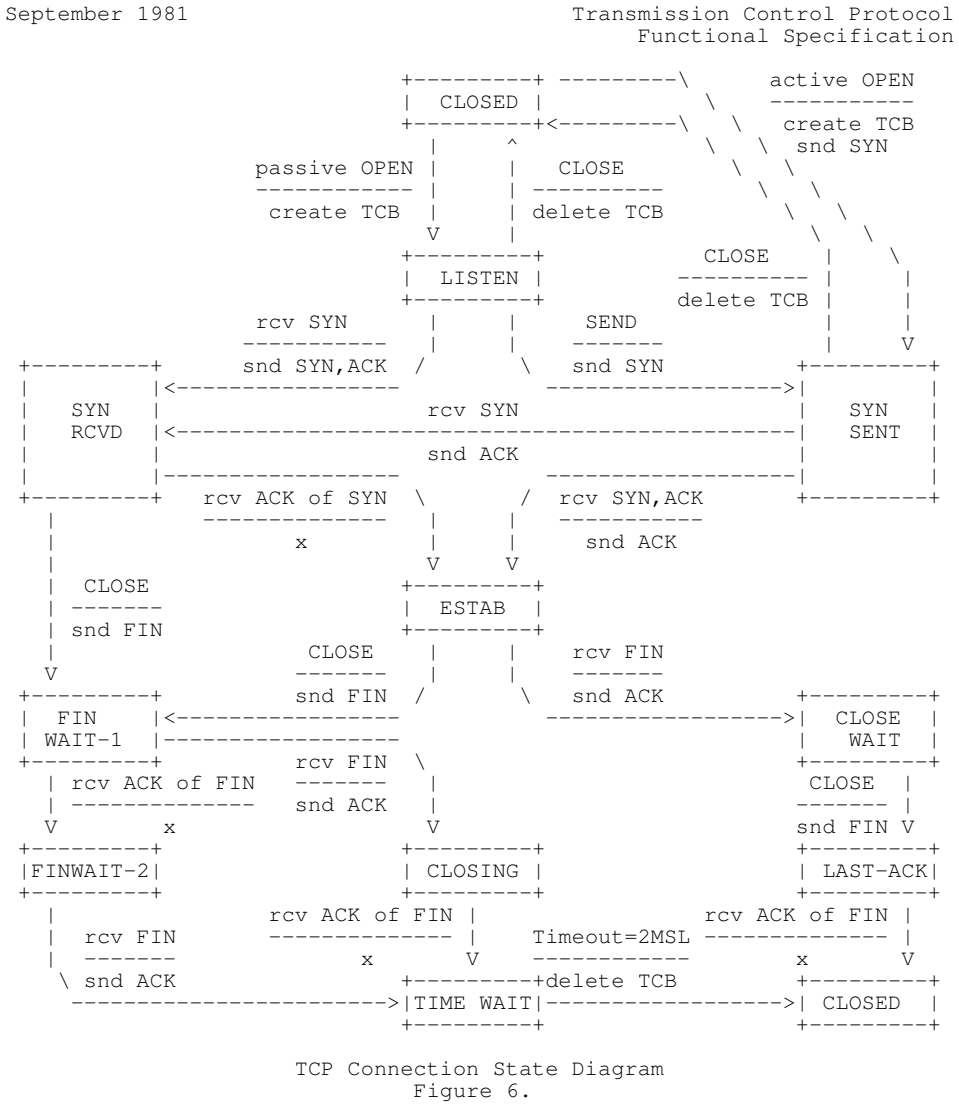

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