Network I/O subsystem in Linux

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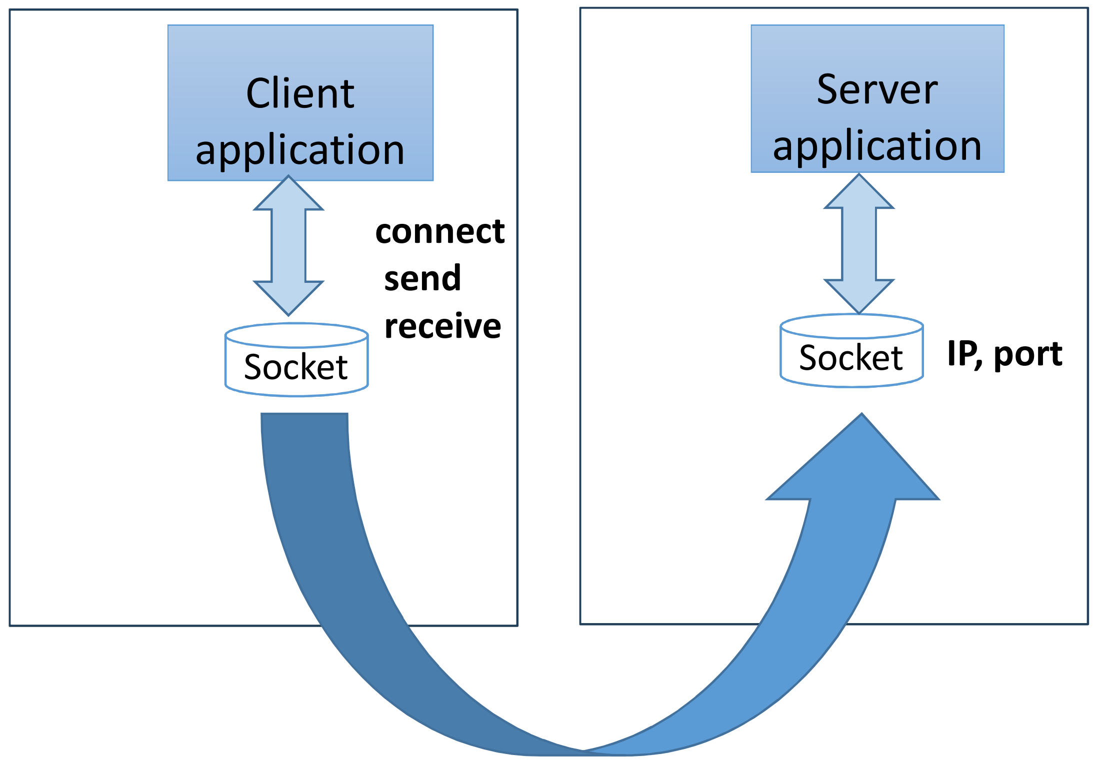
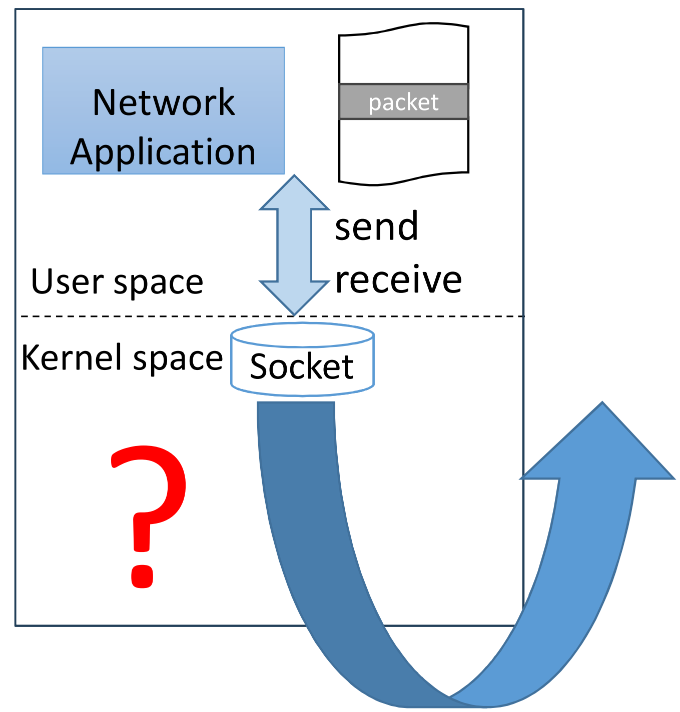
Networking applications

- Networking applications: web server, email client, browser etc..
- Exchange network packets via APIs like sockets
- Servers open sockets at well known IP address + port number
- Socket of web client connects to socket at web server, send and receive messages



What happens inside the kernel?

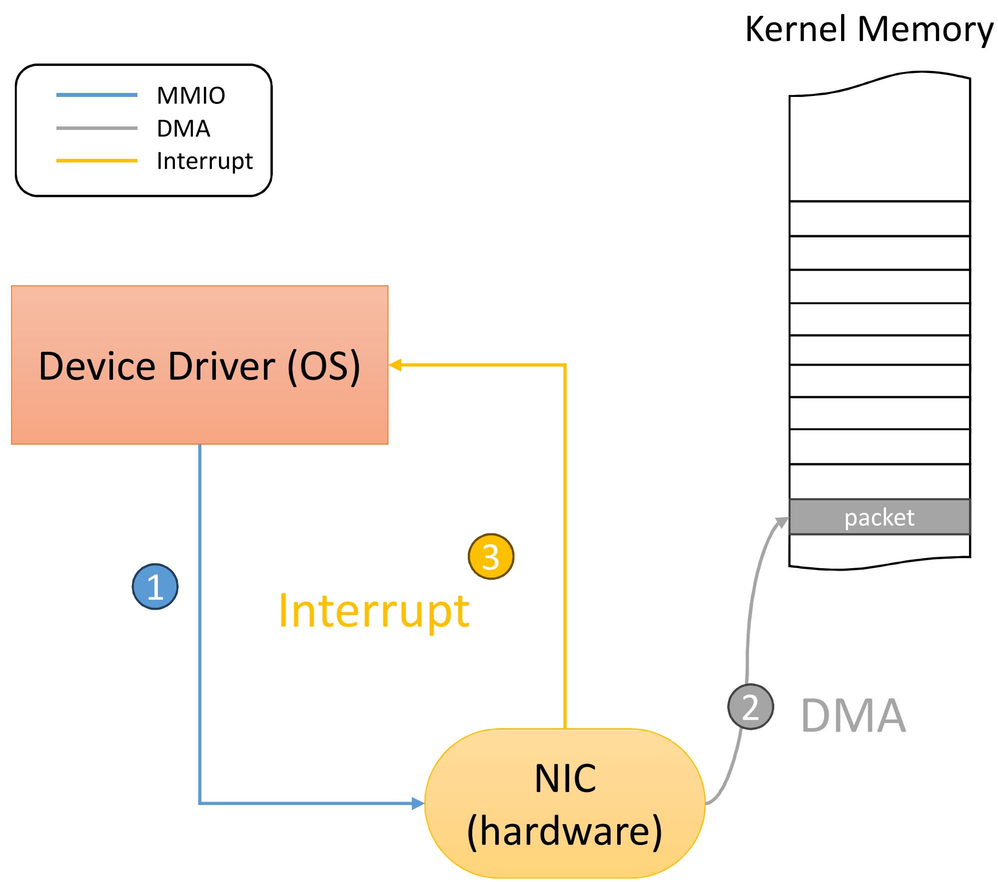
- What happens when you send and receive data through a socket?
- The story of what happens over the network will be covered in your networking course
- What happens at the sender and receiver end host kernel network stack?
- Many recent advances, to help kernel keep up with increasing network speeds



Outside end host: switching, routing, congestion control

Device drivers

- Device driver manages interaction between NIC (network interface card) and software
- Configures NIC via memory mapped I/O (MMIO)
- NIC performs Direct Memory Access (DMA) of network packets into kernel memory
- NIC raises interrupt to indicate reception of packets
- We will discuss only RX path here



Interrupt handling

- How are interrupts handled?
  - CPU is running process P and interrupt arrives
  - CPU saves context of P, runs OS code to handle interrupt in kernel mode
  - Restore context of P, resume P in user mode
- Interrupt handling code is part of OS device drivers
- Network device drivers handle interrupts from NICs

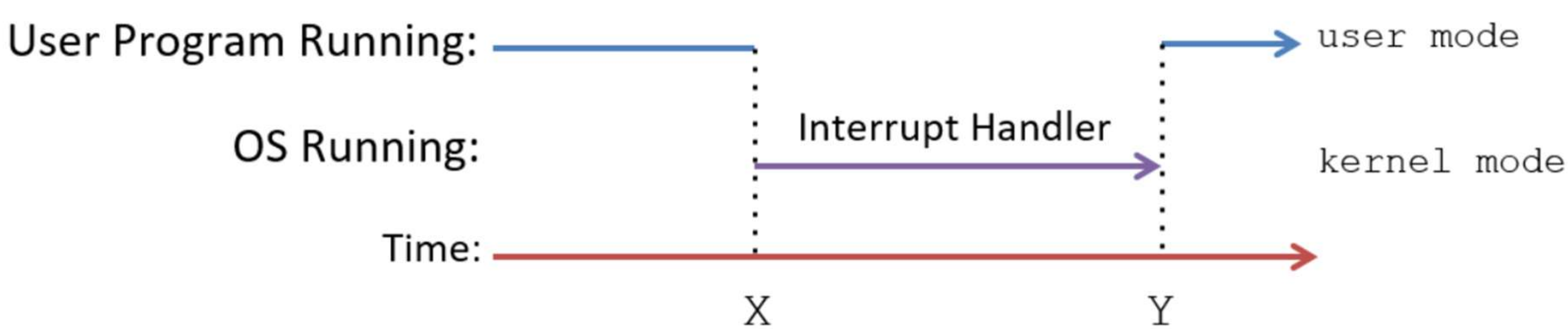


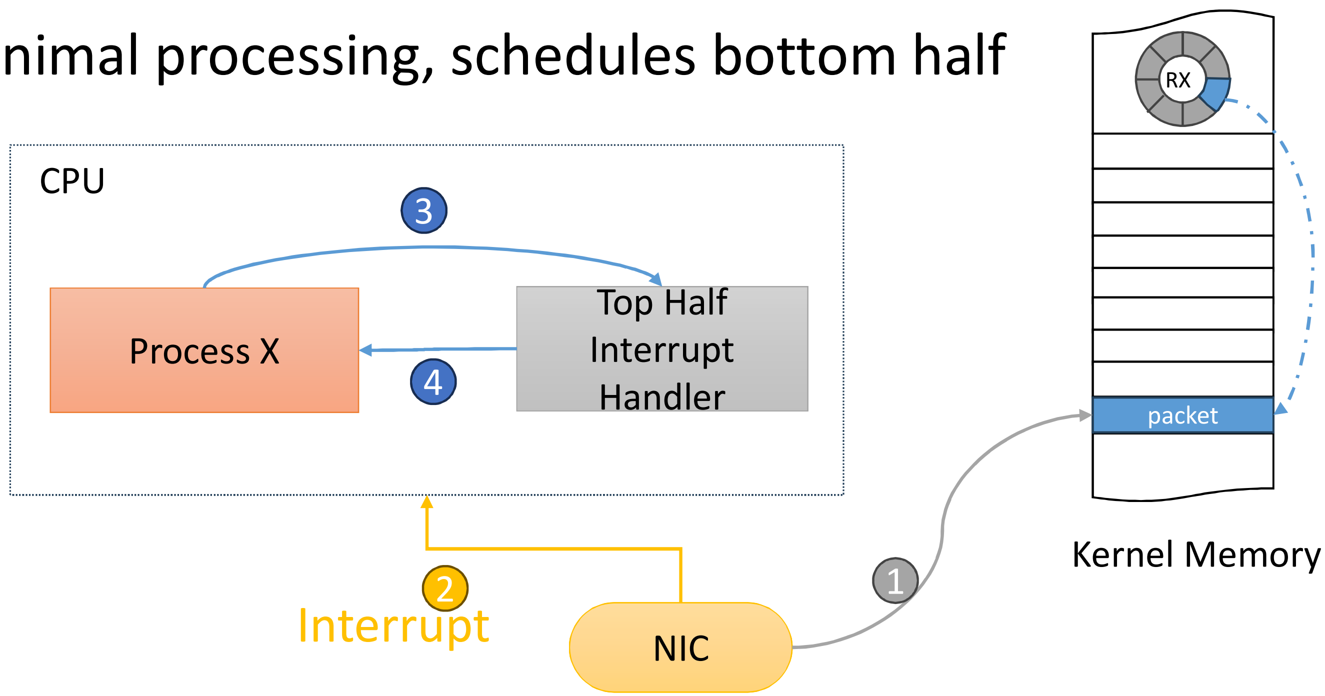
Image credit: Dive into Systems, by Mathews, Newhall, Webb

Network Interrupt handling

- Interrupt handling from NIC involves lot of work
  - Processing information about the network, congestion control, …
- To avoid excessive disruption to interrupted process, NIC interrupt handling split into two parts
- Top half interrupt handler acknowledges interrupt, does minimal processing, disables future interrupts
- Top half schedules a kernel process for full interrupt handling, called bottom half interrupt handler
- Bottom half processes all packets received so far, re-enables interrupts

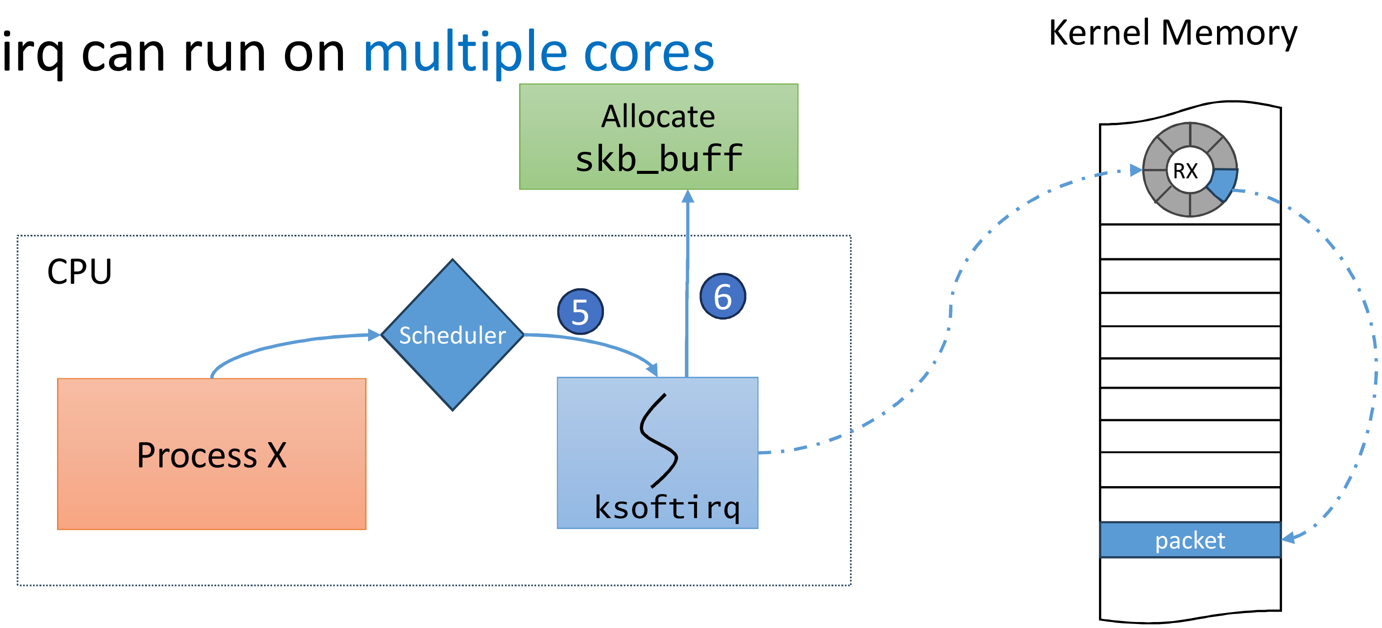
Device driver rings

- NIC and kernel exchange information about packets via TX/RX “rings”
- RX ring: circular array containing pointers to received packets
- NIC does DMA, updates pointer in RX ring, interrupts
- Top half does minimal processing, schedules bottom half



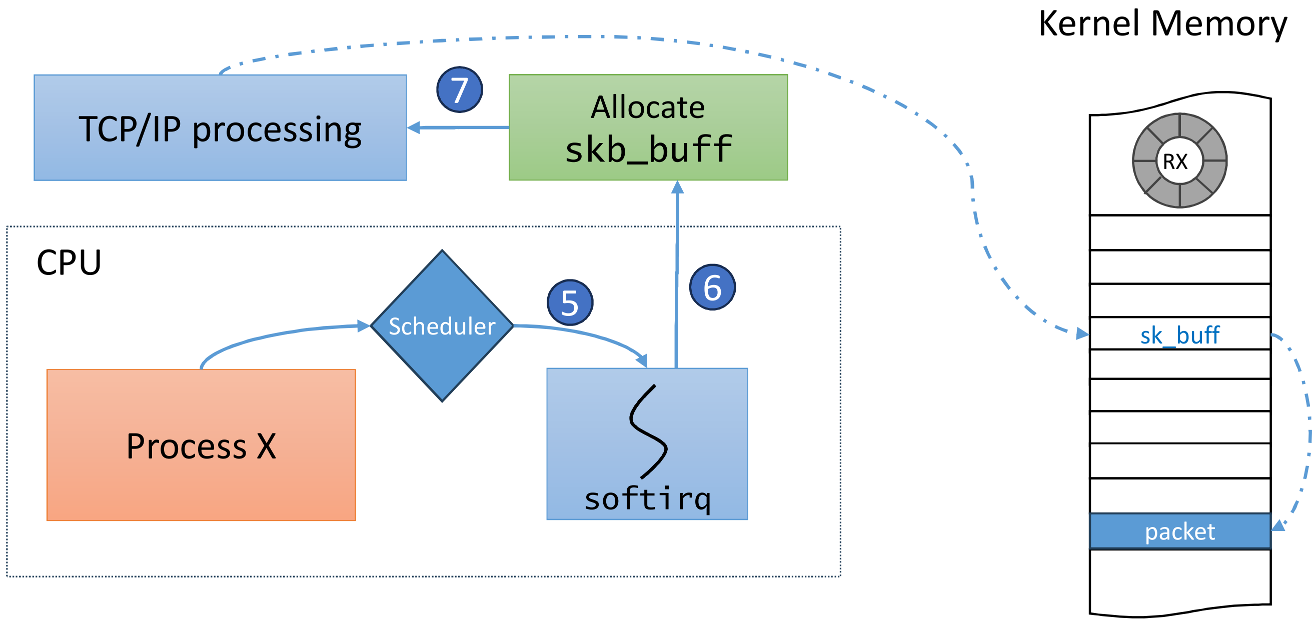
Bottom half interrupt handler

- Bottom half or ksoftirq process scheduled when CPU is free
- Processes all packets collected in the RX ring since the last round
  - Allocates socket buffer (sk_buff) structure for each packet
  - Socket buffer contains pointer to different fields (headers) in the packet
- Interrupt + ksoftirq can run on multiple cores



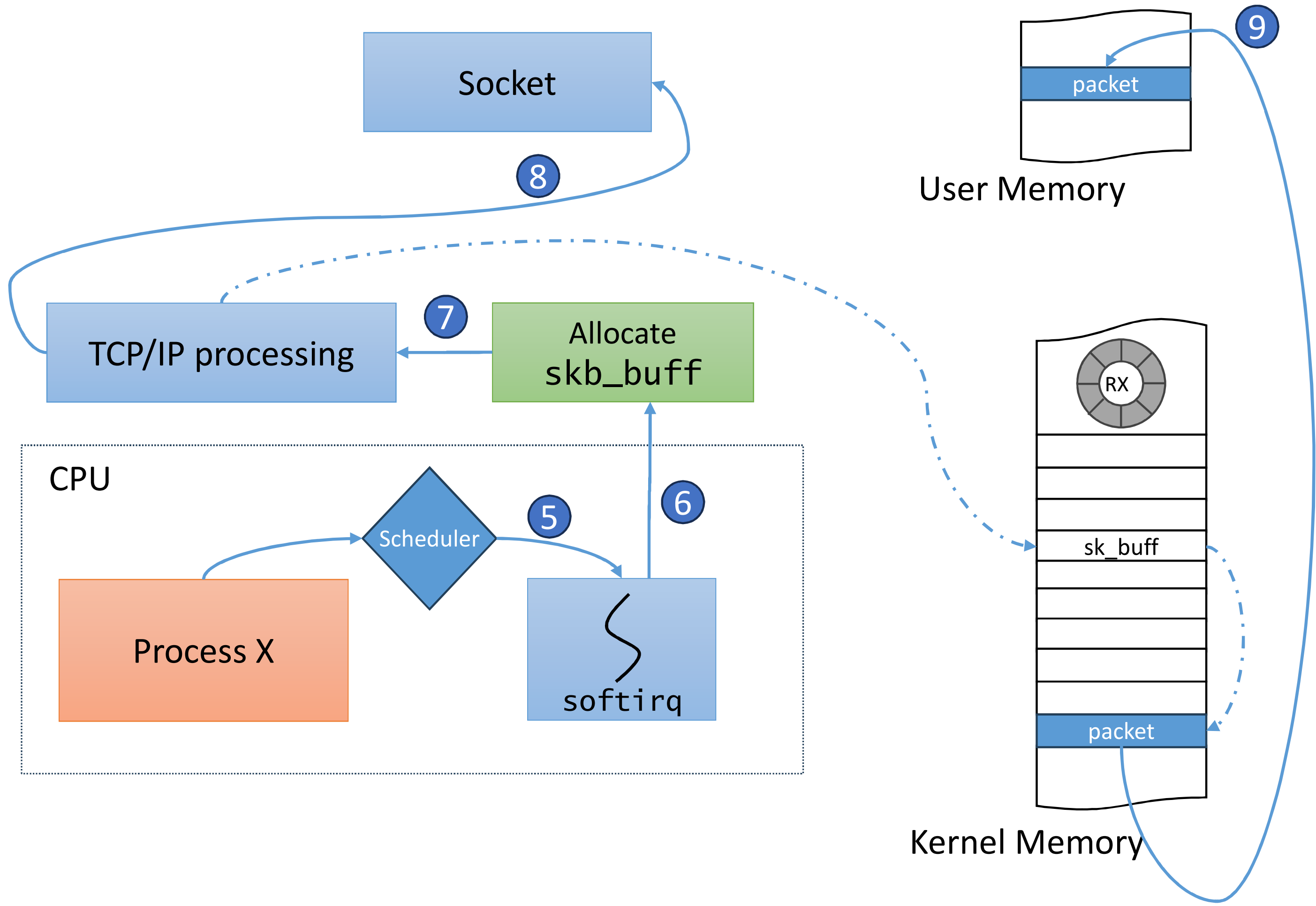
Network layer processing

- Bottom half interrupt handler performs all the network processing
  - Parsing and checking packet headers in sk_buff structure
  - IP routing, TCP reliability and congestion control algorithms (you will learn more about this in the networking course)



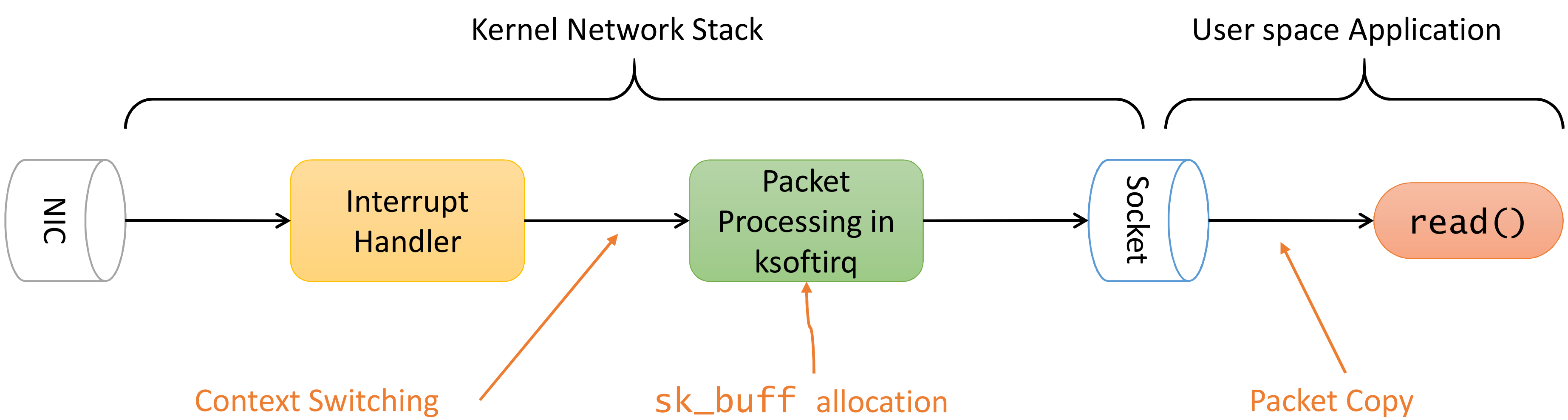
Packet copy to sockets

- Packet headers (port number) used to map received packet to socket
- On read from application, packet payload copied from kernel memory to user memory



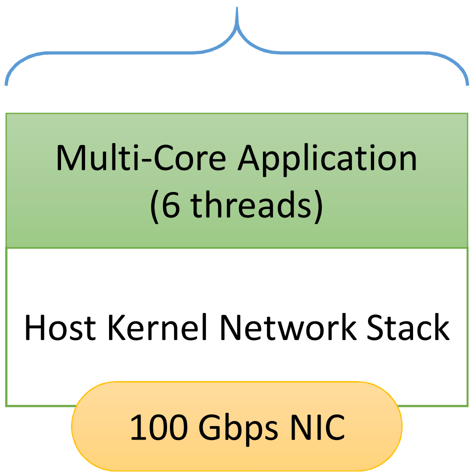
Overheads of the Linux network stack

- Interrupt handling, transition across user and kernel mode
- Context switching from application to ksoftirq
- Packet copy from kernel to user space



Need for alternate fast network I/O tchniques

Max throughput possible is ~15 Gbps [1]

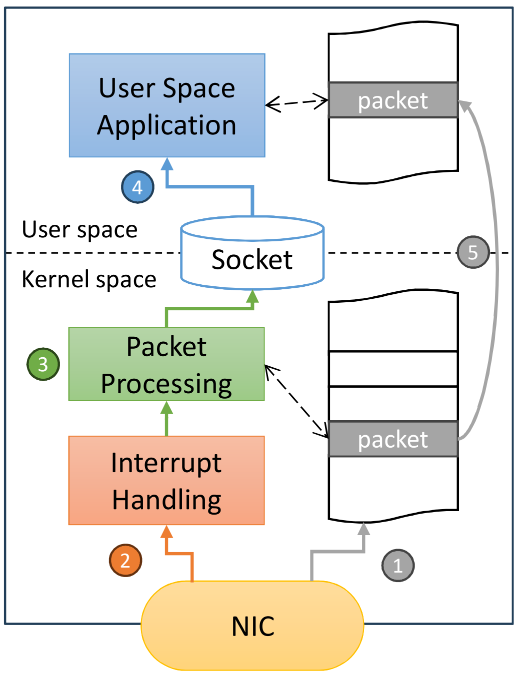


Throughput << NIC Line Rate

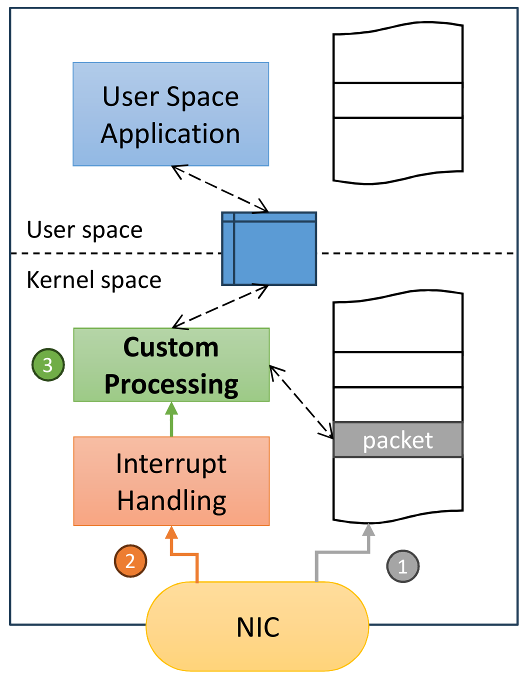
- Multi-threaded applications cannot easily achieve line rate in modern high-speed NICs, especially with small-sized packets
- Techniques to improve processing speed include kernel bypass techniques (directly DMA packets into user space) and using polling-mode device drivers
- Possible to process 100s of Gbps easily in software using such techniques

[1] T. Høiland-Jørgensen et al., "The eXpress data path: fast programmable packet processing in the operating system kernel"

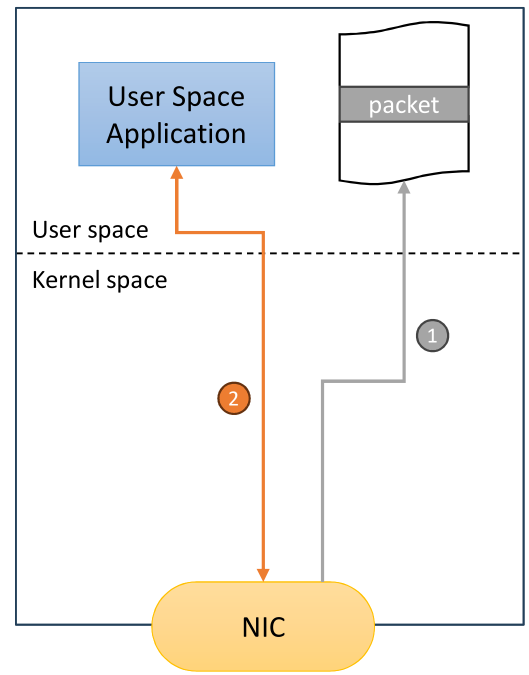
Fast I/O techniques



Generic Kernel Network Stack
High packet processing overheads



In-Kernel Program Offload (eBPF)
Push some extra application functionality into the kernel



Kernel Bypass (DPDK / AFXDP)
Get packets directly into user space application

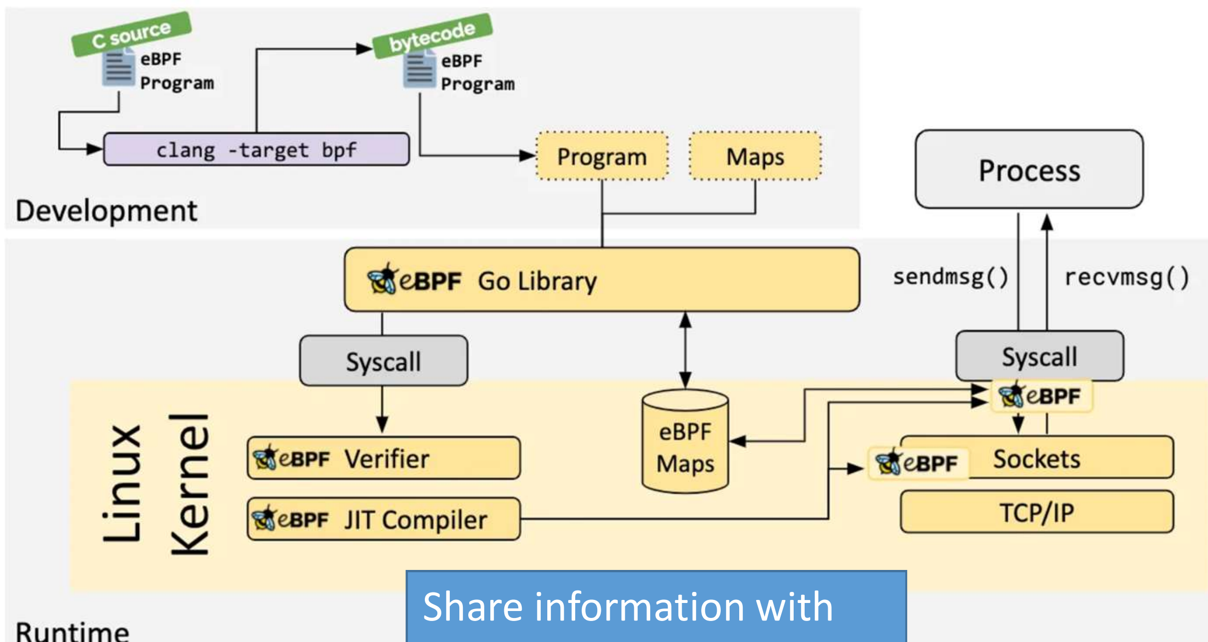
In-kernel packet processing with eBPF

- eBPF (extended Berkeley Packet Filter) is a way to embed custom packet processing code in the kernel safely at specific hook points

User writes C-like code and loads into eBPF hooks

Code verified to be safe (does not crash kernel)

Compiled byte code loaded at kernel hook points



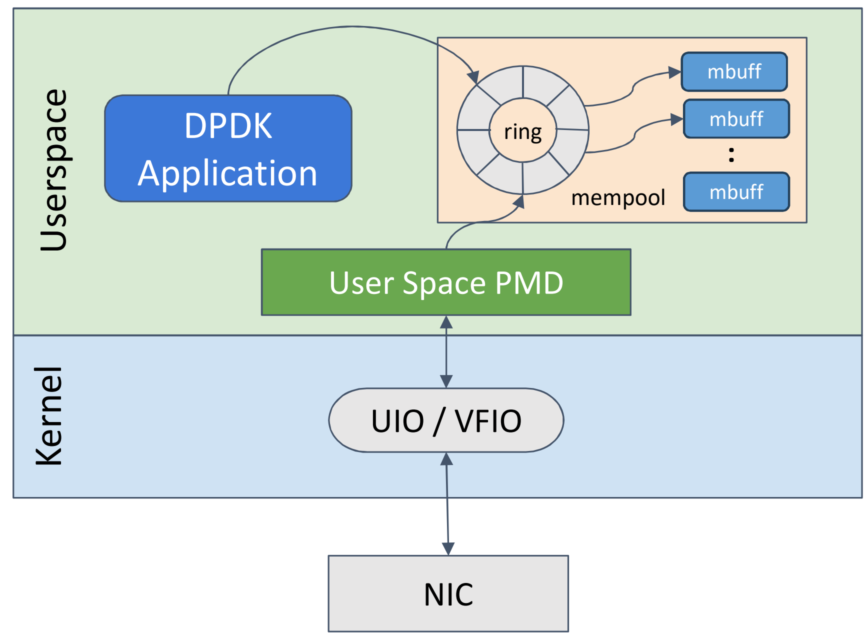
Share information with userspace via eBPF maps

User's compiled code runs inside kernel at desired hook points

Image source: [ebpf.io]

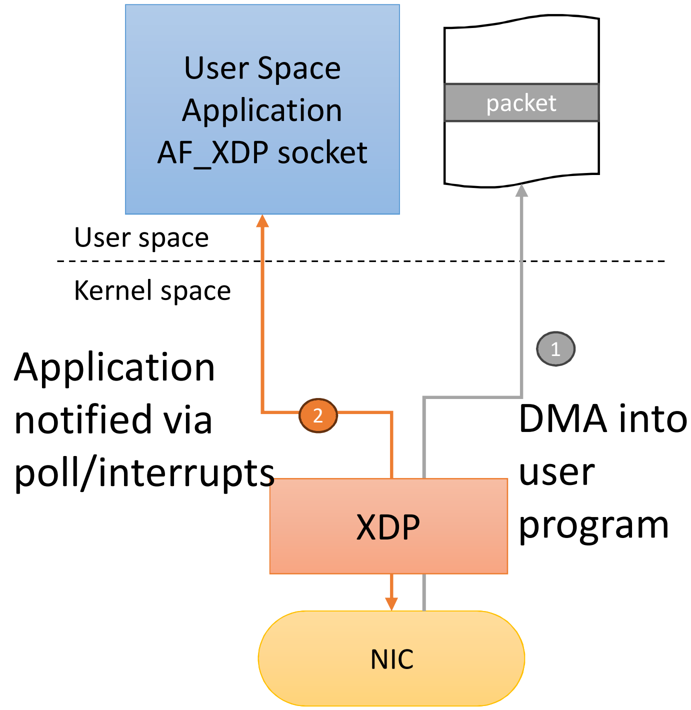
Kernel bypass with DPDK

- Another widely used kernel bypass mechanism
- Poll mode driver in userspace, kernel driver is just passthrough
  - Polls device, fetches and processes batches of packets
  - Packet buffers in user space pre-allocated buffers, huge pages
- Pros: Minimal involvement of kernel, high packet processing rates
- Cons: kernel tools don't work anymore, hard to co-exist with other apps



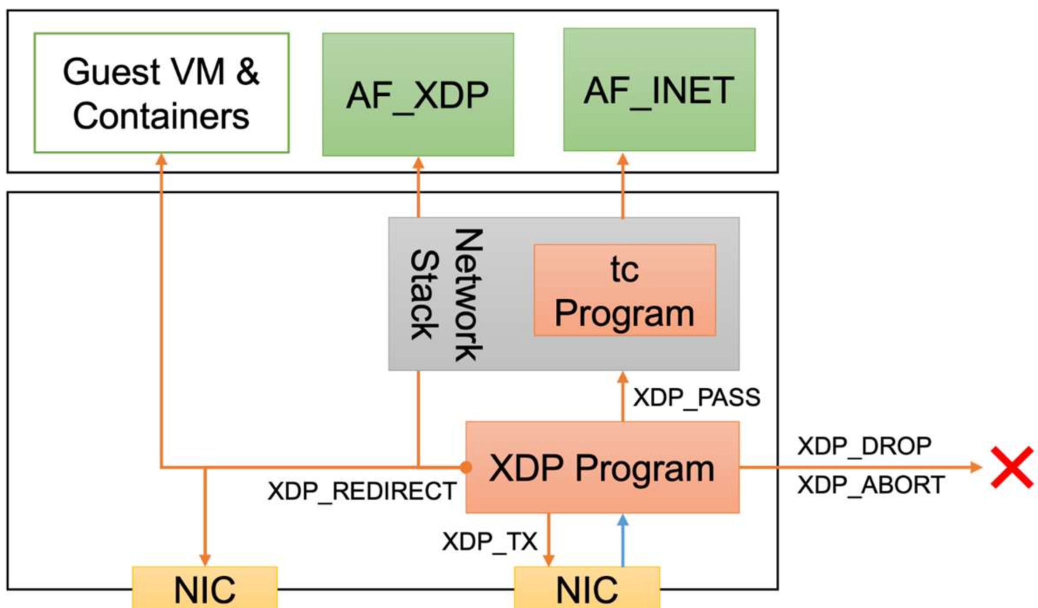
Kernel bypass with AF_XDP

- Regular sockets (AF_INET) receive packets after TCP/IP processing
- AF_XDP is special type of socket that can receive packets directly from XDP hook
  - Packet DMA directly into user space (with driver support), no extra copy, no kernel stack processing overhead
  - Program at XDP hook notifies user space app via poll/interrupt mechanisms
- Higher throughputs possible, while allowing kernel some control



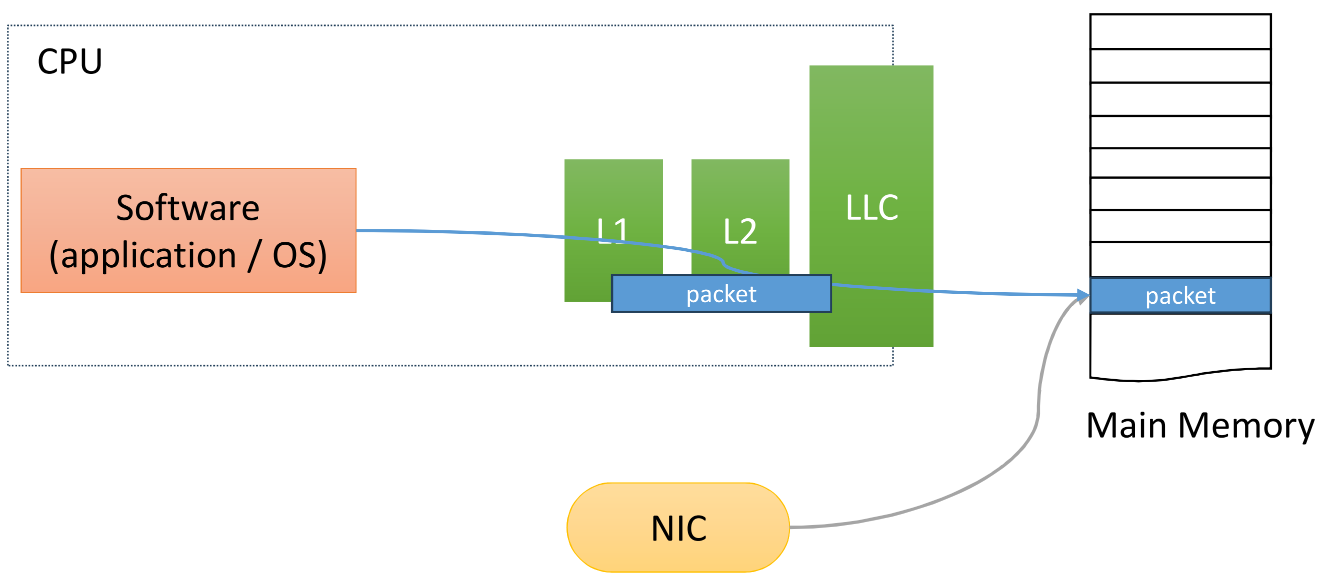
eBPF, XDP, AF_XDP – the connection

- eBPF programs can be safely embedded inside specific hook points to add custom functionality to kernel network stack
- eBPF program at XDP hook can also redirect packets to AF_XDP sockets for processing inside userspace application



Another problem: memory access bottleneck

- Memory wall: DRAM speeds have not increased as much as CPU or network hardware
- On high speed network links, only few nanoseconds budget per packet, but accessing main memory takes hundreds of nanosec



Direct Cache Access / DDIO

- Direct Cache Access (Intel's DDIO): NIC writes packet directly into CPU caches, and does not DMA into main memory
- User/kernel software can access packet quickly from cache
- Leads to much faster network packet processing