Operating Systems Design
16. Networking: Sockets

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Sockets

- IP lets us send data between machines
- TCP & UDP are *transport layer* protocols
  - Contain **port number** to identify transport endpoint (application)
- The most popular abstraction for transport layer connectivity: **sockets**
  - Developed at UC Berkeley

Sockets

Attempt at a generalized IPC model

Goals:

- communication between processes should not depend on whether they are on the same machine
- efficiency
- compatibility
- support different protocols and naming conventions
  - Not just IP networking

Socket

Abstract object from which messages are sent and received

- Looks like a file descriptor
- Application can select particular style of communication
  - Virtual circuit, datagram, message-based, in-order delivery
- Unrelated processes should be able to locate communication endpoints
  - Sockets can have a *name*
  - Name should be meaningful in the communications domain

Programming with sockets

Socket-related system calls

- Sockets are the interface the operating system provides for access to the network

- Next: a connection-oriented example

Step 1

Create a socket

```
int s = socket(domain, type, protocol)
```

AF_INET

SOCK_STREAM
SOCK_DGRAM

useful if some families have more than one protocol to support a given service

Conceptually similar to open BUT
- *open* creates a new reference to a possibly existing object
- *socket* creates a new instance of an object

Step 2

Name the socket (assign address, port)

```
int error = bind(s, addr, addrlen)
```

socket

Address structure
`struct sockaddr*`

length of address structure

Step 3a (server)

Set socket to be able to accept connections

```
int error = listen(s, backlog)
```

socket

queue length for pending connections

Step 3b (server)

Wait for a connection from client

```
int snew = accept(s, clntaddr, &clntalen)
```

socket

pointer to address structure

length of address structure

new socket
for this session

s is only used for managing the queue of connection requests

Step 3 (client)

Connect to server

```
int error = connect(s, svraddr, svraddrlen)
```

socket

address structure
`struct sockaddr*`

length of address structure

Step 4

Exchange data

Connection-oriented I/O

`read/write`
`recv/send` *(extra flags)*

Connectionless I/O: no need for *connect, listen, accept*

`sendto`/`recvfrom`
`sendmsg`/`recvmsg`

Step 5

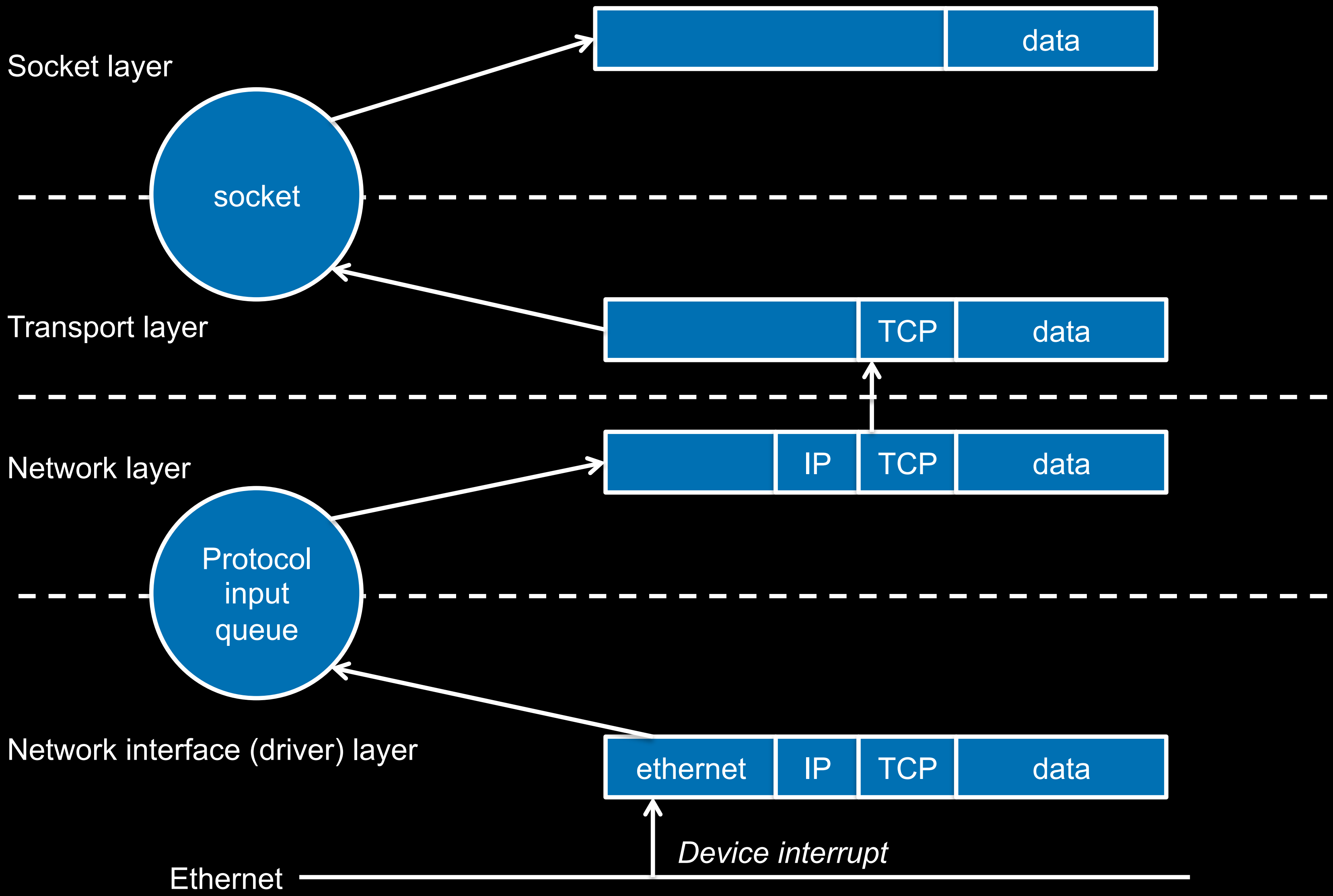
Close connection

```
shutdown(s, how)
```

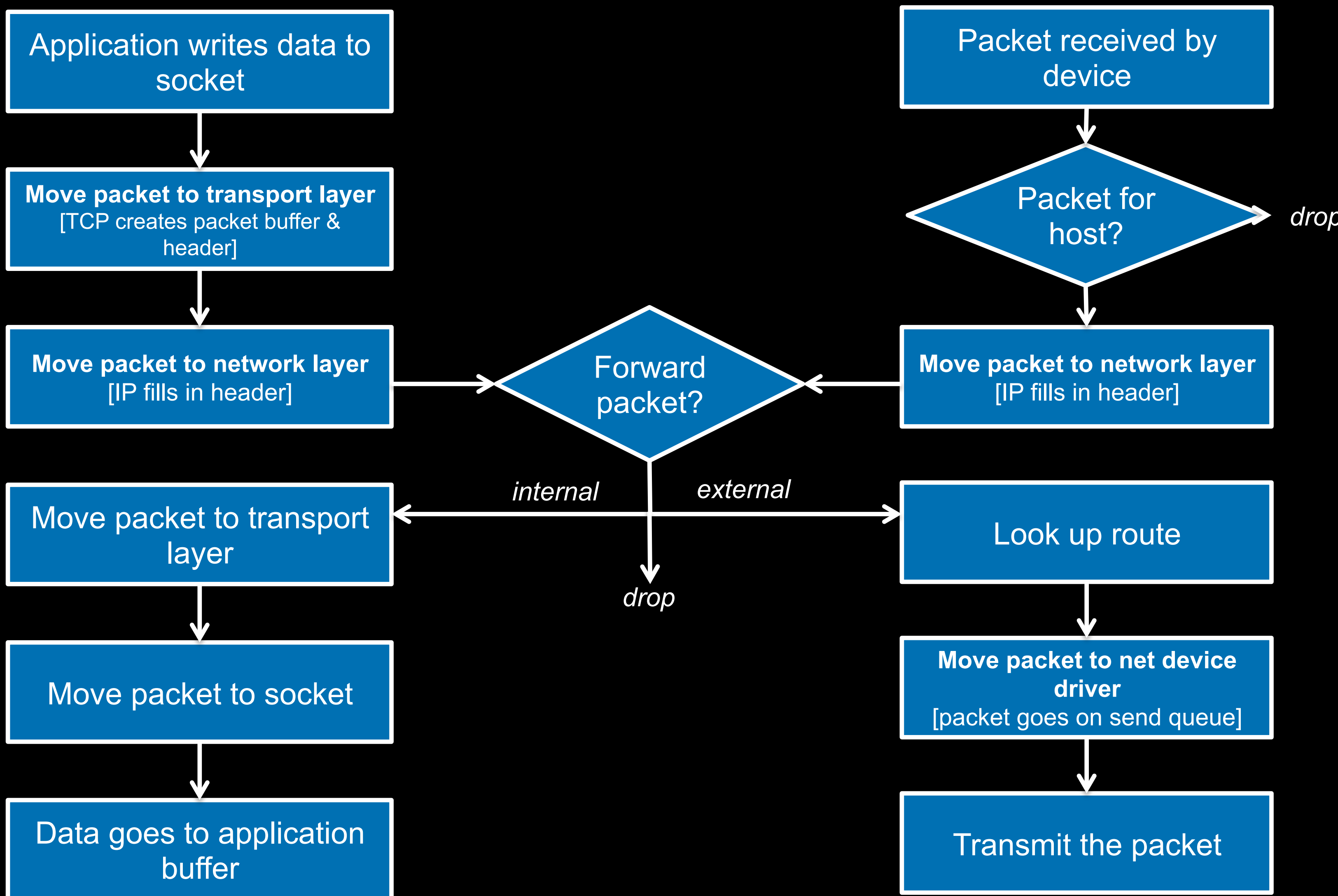
how:
0: can send but not receive
1: cannot send more data
2: cannot send or receive (=0+1)

Socket Internals

Logical View



Data Path



Adapted from http://kernelnewbies.org/Documents/LinuxIPNetworking

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OS Network Stack

System call Interface		Socket-related system calls
Generic network interface		Sockets implementation layer
Network Protocols	Transport Layer	TCP/IPv4, UDP/IPv4, TCP/IPv6
	Network Layer	IPv4, IPv6
Abstract Device Interface		“netdevice”, queuing discipline
Device Driver	Link Layer	Ethernet, Wi-Fi, SLIP

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System call interfaces for accessing sockets

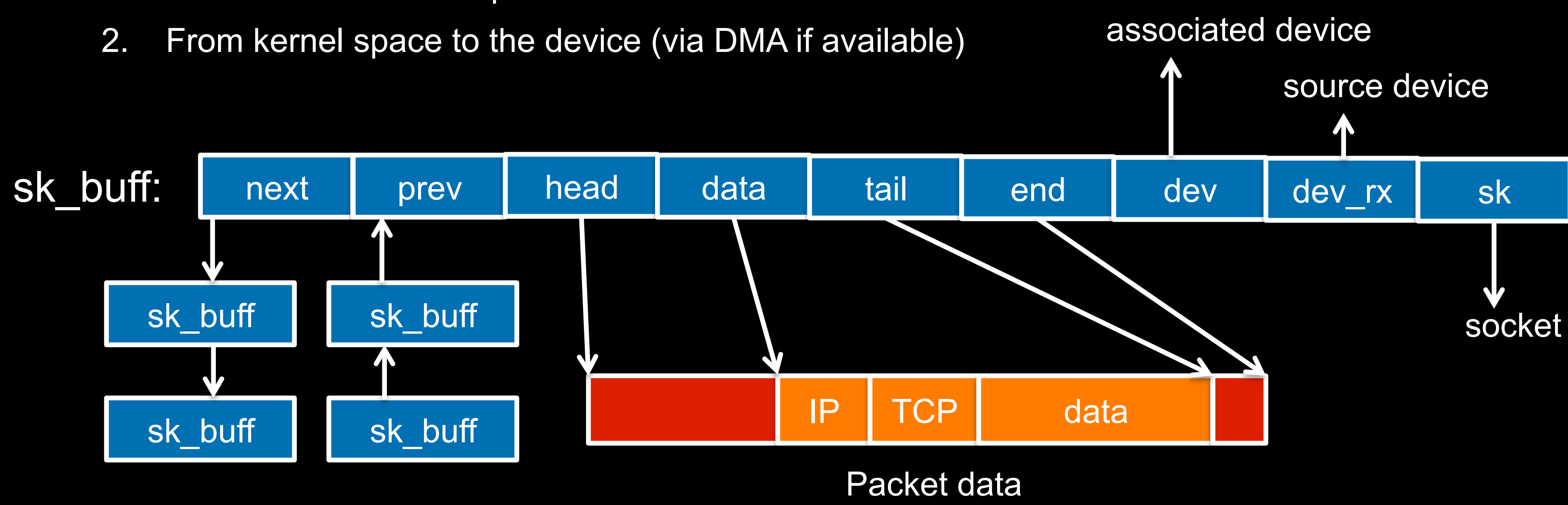
- Two ways to communicate with the network:
  - Socket-specific call (e.g., *socket, bind, shutdown*)
    - Directed to sys_socketcall (socket.c)
    - Goes to the target function
  - File descriptor call (e.g., *read, write, close*)
    - File descriptor ≡ socket
      - Sockets reside in the process's file table
    - Direct parallel of the VFS structure
      - A socket's *f_ops* field points to a set of functions for socket operations
- A `socket` structure acts as a queuing point for data being transmitted & received
  - A socket has send and receive queues associated with it
    - High & low watermarks to avoid resource exhaustion

Sockets layer

- All network communication takes place via a socket
- Two socket structures – one within another
  1. Generic sockets (*aka* BSD sockets) – `struct socket`
  2. Protocol-specific sockets (INET socket) – `struct sock`
- *`socket`* structure
  – Keeps all the state of a socket including the protocol and operations that can be performed on it
  – Some key members of the structure:
    - struct proto_ops *ops: protocol-specific functions that implement socket operations
      – Common functions to support a variety of protocols
      – TCP, UDP, IP, raw ethernet, other networks
    - struct inode *inode: points to in-memory inode associated with the socket
    - struct sock *sk: protocol-specific (e.g., INET) socket
      – E.g., this contains TCP/IP and UDP/IP specific data for an INET (Internet Address Domain) socket

Socket Buffer: `struct sk_buff`

- Component for managing the data movement for sockets through the networking layers
  - Contains packet & state data for multiple layers of the protocol stack
- Don't waste time copying parameters & packet data from layer to layer of the network stack
- Data sits in a socket buffer (struct sk_buff)
- As we move through layers, data is only copied twice:
  1. From user to kernel space
  2. From kernel space to the device (via DMA if available)



Socket Buffer: `struct sk_buff`

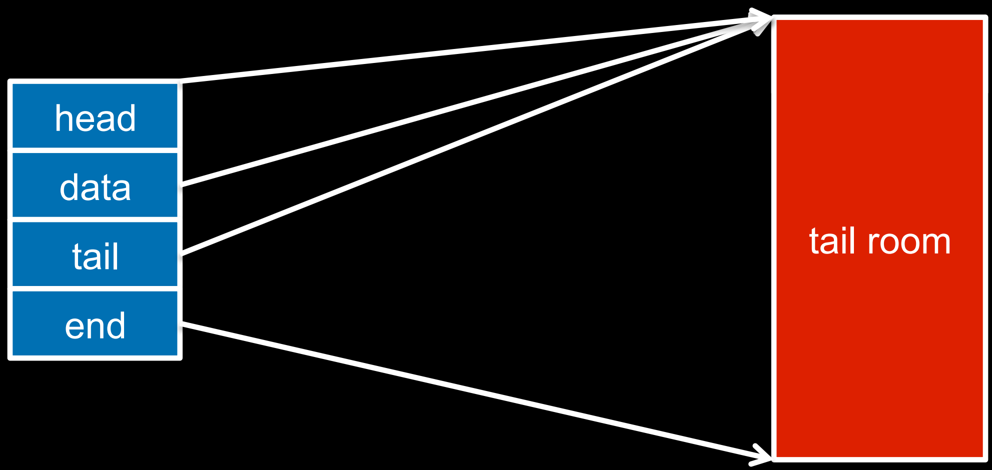
- Each sent or received packet is associated with an sk_buff:
  - Packet data in *`data->`*, *`tail->`*
  - Total packet buffer in *`head->`*, *`end->`*
  - Header pointers (MAC, IP, TCP header, etc.)

Add or remove headers without reallocating memory

- Identifies device structure (`net_device`)
  - `rx_dev`: points to the network device that received the packet
  - `dev`: identifies net device on which the buffer operates
    - If a routing decision has been made, this is the outbound interface

- Each socket (connection stream) is associated with a linked list of sk_buffs

Keeping track of packet data

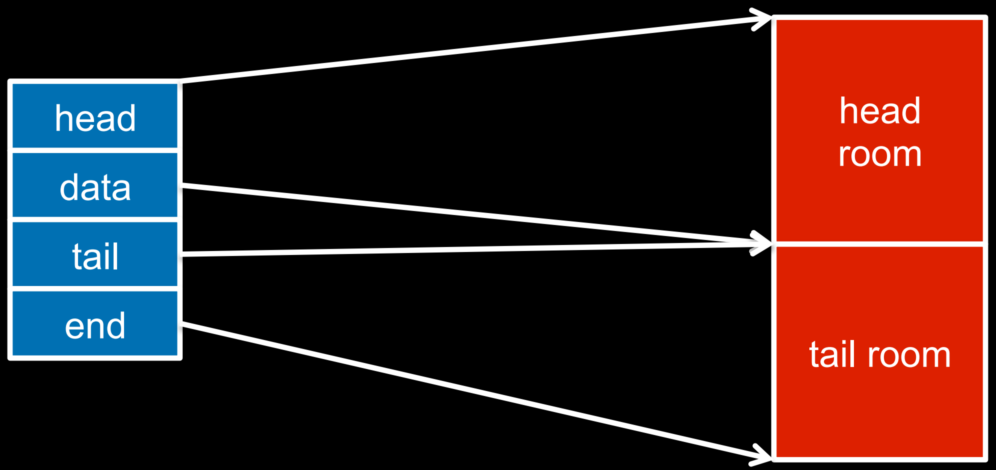


Allocate new socket buffer data

```
skb = alloc_skb(len, GFP_KERNEL);
```

No packet data: head = data = tail

Keeping track of packet data

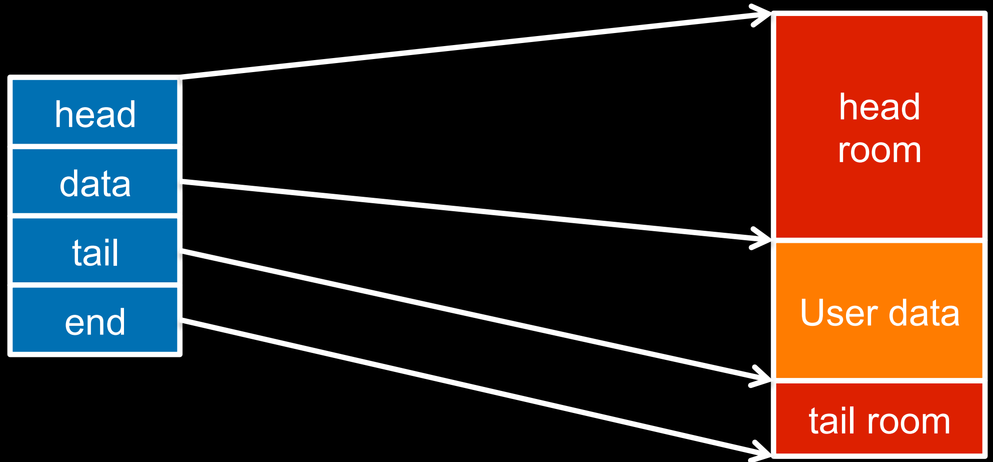


Make room for protocol headers.
    skb_reserve(skb, header_len)

For IPv4, use sk->sk_prot->max_header

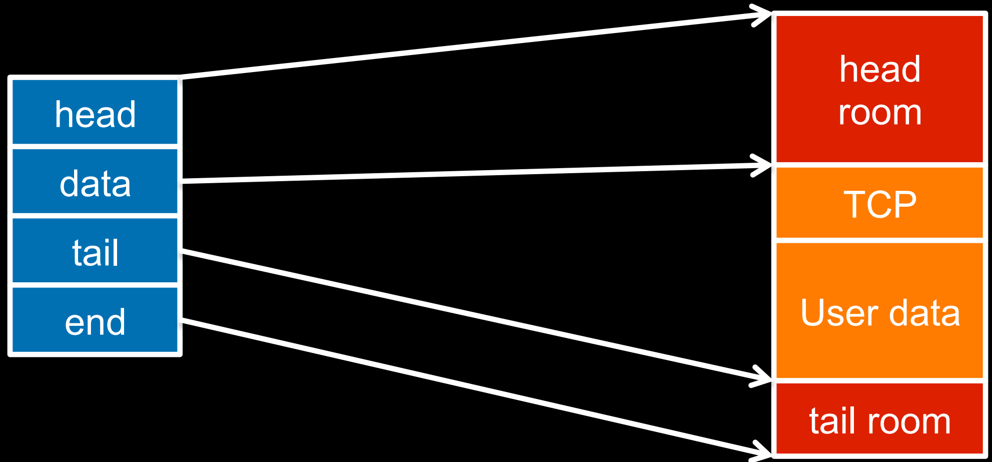
Data size is still 0

Keeping track of packet data



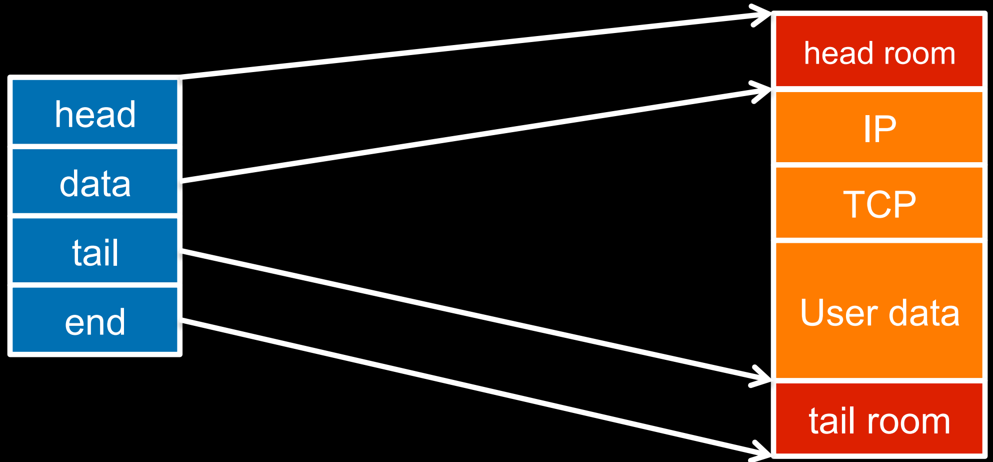
Add user data

Keeping track of packet data



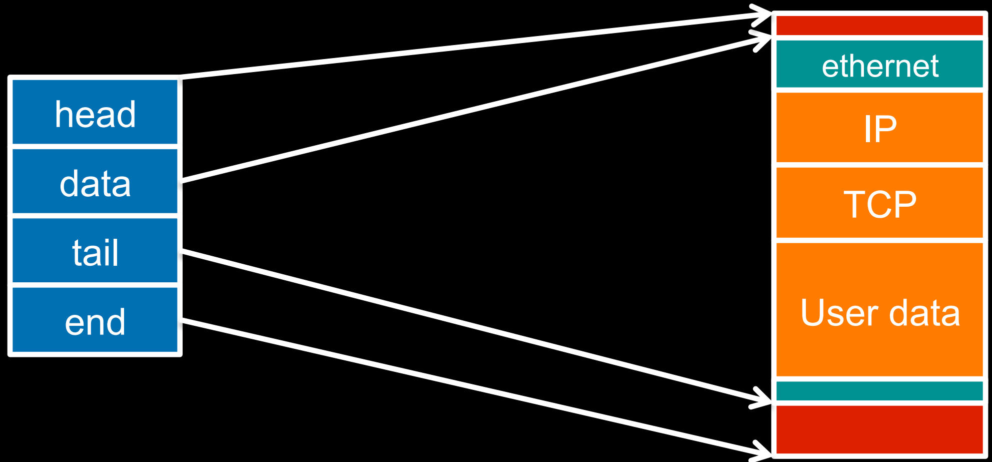
Add TCP header

Keeping track of packet data



Add IP header

Keeping track of packet data



Add ethernet header

The outbound packet is complete!

Network protocols

- Define the specific protocols available (e.g., TCP, UDP)
- Each networking protocol has a structure called *proto*
  - Associated with an “address family” (e.g., AF_INET)
  - Address family is specified by the programmer when creating the socket
  - Defines socket operations that can be performed from the sockets layer to the transport layer
    - *Close, connect, disconnect, accept, shutdown, sendmsg, recvmsg,* etc.
- Modular: one module may define one or more protocols
- Initialized & registered at startup
  - Initialization function: registers a family of protocols
  - The *register* function adds the protocol to the active protocol list
- Additional protocols can be added by calling *inet_register_proto_sw*

Abstract device interface

- Layer above network device drivers
- Common set of functions for low-level network device drivers to operate with the higher-level protocol stack

Abstract device interface

- Send a packet to a device
  - Send sk_buff from the protocol layer to a device
    - dev_queue_xmit function
    - enqueues an sk_buff for transmission to the underlying driver
    - Device is defined in sk_buff
      - Device structure contains a method hard_start_xmit: driver function for actually transmitting the data in the sk_buff

- Receive a packet from a device & send to protocol stack
  - Receive an sk_buff from a device
    - Driver receives a packet and places it into an allocated sk_buff
    - Sk_buff passed to the network layer with a call to netif_rx
    - Function enqueues the sk_buff to an upper-layer protocol's queue for processing through netif_rx_schedule

Device drivers

- Drivers to access the network device
  - Examples: ethernet, 802.11b/g/n, SLIP
- Modular, like other devices
  - Described by `struct net_device`
- Initialization
  - Driver allocates a `net_device` structure
  - Initializes it with its functions
    - `dev->hard_start_xmit`: defines how to transmit a packet
      - Typically the packet is moved to a hardware queue
    - Register interrupt service routine
  - Calls *`register_netdevice`* to make the device available to the network stack

Sending a message

- Write data to socket
- Socket calls appropriate *send* function (typically INET)
  - Send function verifies status of socket & protocol type
  - Sends data to transport layer routine (typically TCP or UDP)
- Transport layer
  - Creates a socket buffer (struct sk_buff)
  - Copies data from user's memory; fills in header (port #, options, checksum)
  - Passes buffer to the network layer (typically IP)
- Network layer
  - Fills in buffer with its own headers (IP address, options, checksum)
  - Look up destination route
  - IP layer may fragment data into multiple packets
  - Passes buffer to link layer: to destination route's device output function
- Link layer (part 1): move packet to the device's xmit queue
- Network driver (link layer part 2)
  - Wait for scheduler to run the device driver
  - Sends the link header
  - Transmit packet via DMA

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Routing

IP Network layer

Two structures:

1. Forwarding Information Base (FIB)
   Keeps track of details for every known route
2. Cache for destinations in use (hash table)
   If not found here then check FIB.

Receiving a message – part 1

- Interrupt from network card: packet received
- Network driver – top half
  - Allocate new `sk_buff`
  - Get data from the hardware buffer into the `sk_buff` (DMA)
  - Call *netif_rx*, the generic network reception handler
    - This moves the sk_buff to protocol processing
    - When netif_rx returns, the service routine is finished
  - Repeat until no more packets in the device buffers

- If the packet queue is full, the packet is discarded
- *netif_rx* is called in the interrupt service routine
  - Must be quick. Main goal: queue the packet.

Receiving a packet – part 2

Bottom half

- Kernel schedules work to go through pending packet queue
- Call *net_rx_action()*
  - Dequeue first `sk_buff` (packet)
  - Go through list of protocol handlers
    - Each protocol handler registers itself
    - Identifies which protocol type they handle
    - Go through each generic handler first
    - Then go through the *receive* function registered for the packet's protocol

Receiving an IP packet – part 3

Network layer

- IP is a registered as a protocol handler for ETH_P_IP packets
  - IP handler will either route the packet, deliver locally, or discard
    - Send either to an outgoing queue (if routing) or to the transport layer
  - Look at protocol field inside the IP packet
    - Calls transport-lever handlers (*tcp_v4_rcv*, *udp_rcv*, *icmp_rcv*, …)
  - IP handler includes Netfilter hooks

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Receiving an IP packet – part 4

Transport layer

- Next stage (usually): *tcp_v4_rcv()* or *udp_rcv()*
  - Check for transport layer errors
  - Look for a socket that should receive this packet (match local & remote addresses and ports)
  - Call *tcp_v4_do_rcv*: passing it the `sk_buff` and socket (sock structure)
    - Adds `sk_buff` to the end of that socket's receive queue
    - The socket may have specific processing options defined
      - If so, apply them
- Wake up the process (ready state) if it was blocked on the socket

Lots of Interrupts!

- Assume:
  - Non-jumbo maximum payload size: 1500 bytes
  - TCP acknowledgement (no data): 40 bytes
  - Median packet size: 413 bytes
- Assume a steady amount of network traffic at:
  - 1 Gbps: ~300 thousand packets/second
  - 100 Mbps: ~30 thousand packets/second
  - 10 Mbps: ~3 thousand packets /second
- Even 9000-byte jumbo frames
  - 1 Gbps: 14,000 packets per second → 14,000 interrupts/second

One interrupt per received packet

Network traffic can generate a LOT of interrupts!!

Interrupt Mitigation: Linux NAPI

- Linux NAPI: “New API” (c. 2009)
- Avoid getting thousands of interrupts per second
  - Disable network device interrupts during high traffic
  - Re-enable interrupts when there are no more packets
- Also, packet throttling:
  - If we get more packets than we can process, leave them in the network card’s buffer and let them get overwritten (same as dropping a packet)

The End

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