Linux Networking

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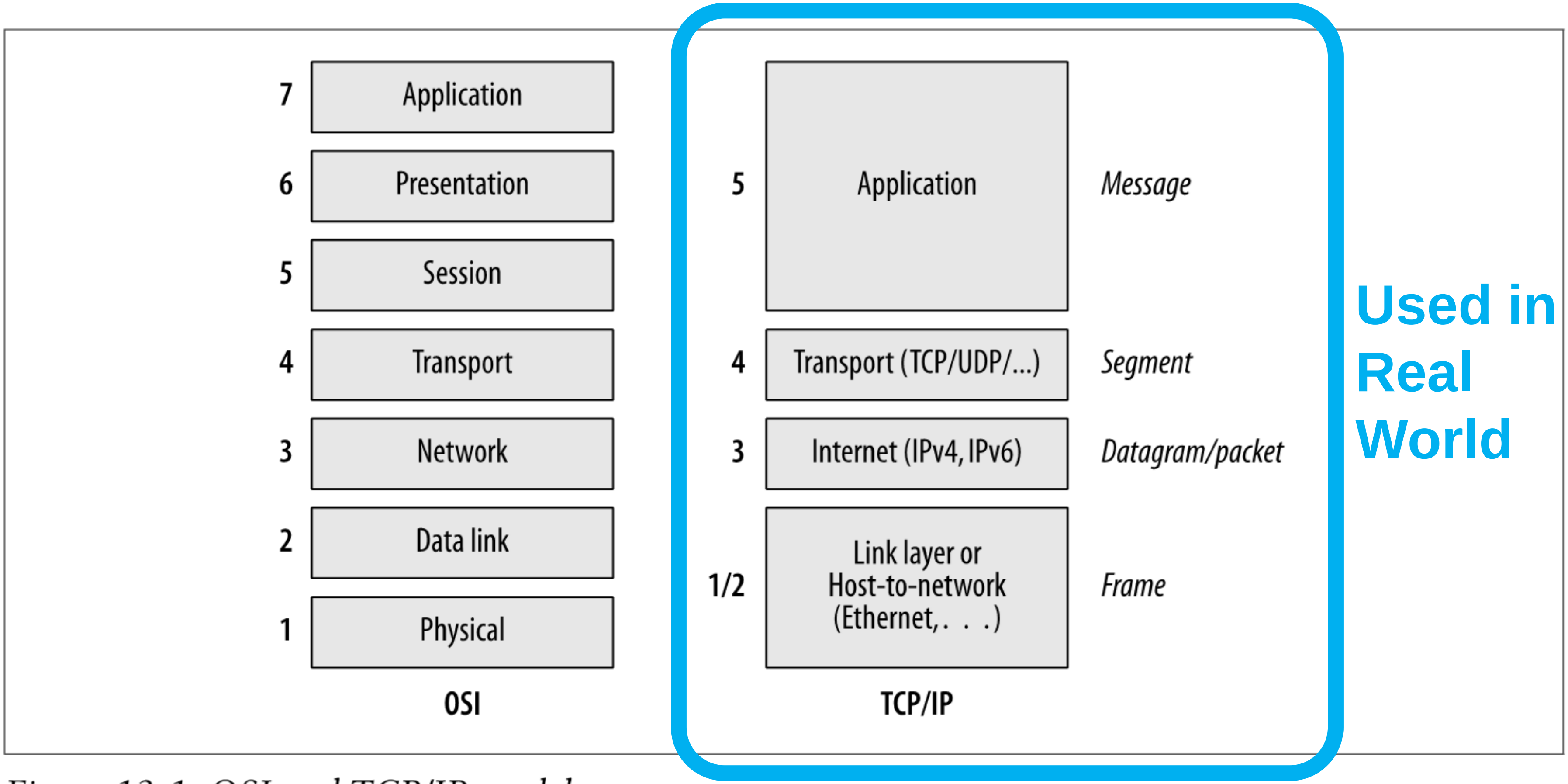
4- to 7-Layer Diagram

- OSI and TCP/IP Stacks (From *Understanding Linux Network Internals*)



Used in Real World

Figure 13-1. OSI and TCP/IP models

Ethernet (IEEE 802.3)

- LAN (Local Area Network) connection
- Simple packet layout:
  - Header
    - Type (e.g., IPv4)
    - source MAC address
    - destination MAC address
    - length (up to 1500 bytes)
    - …
  - Data block (payload)
  - Checksum
- Higher-level protocols “wrapped” inside payload
- “Unreliable” – no guarantee packet will be delivered

Internet Protocol (IP)

- 2 flavors: Version 4 and 6
  - Version 4 widely used in practice
  - Version 6 should be used in practice – but isn’t
    - Public IPv4 address space is practically exhausted (see arin.net)
- Provides a network-wide unique address (IP address)
  - Along with netmask
  - Netmask determines if IP is on local LAN or not
- If destination not on local LAN
  - Packet sent to LAN’s ***gateway***
  - At each gateway, payload sent to next hop

Address Resolution Protocol (ARP)

- IPs are logical (set in OS with ***ifconfig*** or ***ipconfig***)
- OS needs to know where (physically) to send packet
  - And switch needs to know which port to send it to
- Each NIC has a MAC (Media Access Control) address
  - "physical" address of the NIC
- OS needs to translate IP to MAC to send
  - Broadcast "who has 10.22.17.20" on the LAN
  - Whoever responds is the physical location
    - Machines can cheat (spoof) addresses by responding
  - ARP responses cached to avoid lookup for each packet

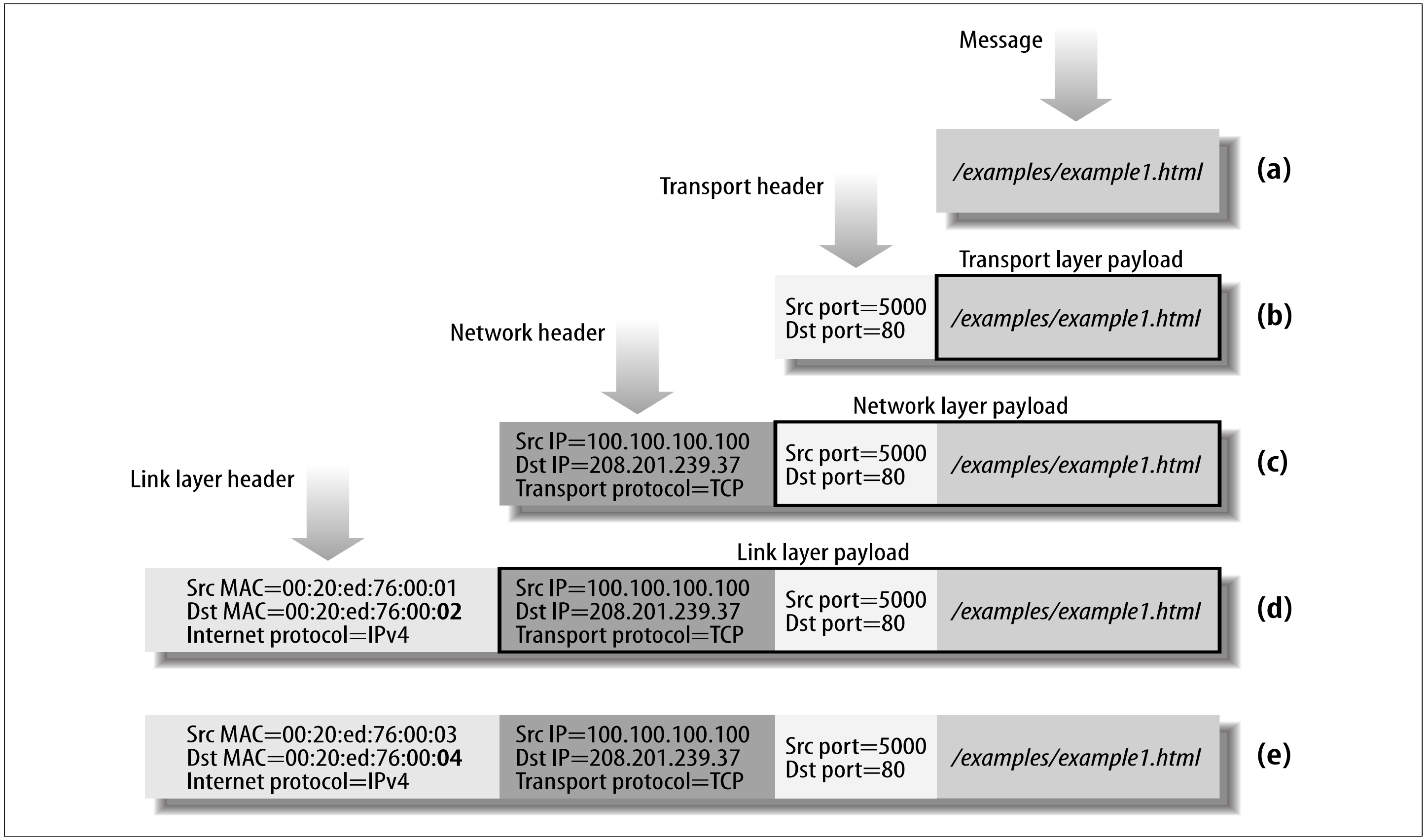
User Datagram Protocol (UDP)

- Applications on a host are assigned a port number
  - A simple integer
  - Multiplexes many applications on one device
  - Ports below 1k reserved for privileged applications
- Simple protocol for communication
  - Send packet, receive packet
  - No association between packets in underlying protocol
    - Application is responsible for dealing with…
      - Packet ordering
      - Lost packets
      - Corruption of content
      - Flow control
      - Congestion

Transmission Control Protocol (TCP)

- Same port abstraction (1-64k)
  - But different ports
  - i.e., TCP port 22 isn’t the same port as UDP port 22
- Higher-level protocol providing end-to-end reliability
  - Transparent to applications
  - Lots of features
    - packet acks, sequence numbers, automatic retry, etc.
  - Pretty complicated

Web Request Example



Message

/examples/example1.html (a)

Transport header

Transport layer payload

Src port=5000
Dst port=80
/examples/example1.html (b)

Network header

Network layer payload

Src IP=100.100.100.100
Dst IP=208.201.239.37
Transport protocol=TCP
Src port=5000
Dst port=80
/examples/example1.html (c)

Link layer header

Link layer payload

Src MAC=00:20:ed:76:00:01
Dst MAC=00:20:ed:76:00:**02**
Internet protocol=IPv4
Src IP=100.100.100.100
Dst IP=208.201.239.37
Transport protocol=TCP
Src port=5000
Dst port=80
/examples/example1.html (d)

Src MAC=00:20:ed:76:00:03
Dst MAC=00:20:ed:76:00:**04**
Internet protocol=IPv4
Src IP=100.100.100.100
Dst IP=208.201.239.37
Transport protocol=TCP
Src port=5000
Dst port=80
/examples/example1.html (e)

Figure 13-4. Headers compiled by layers: (a…d) on Host X as we travel down the stack; (e) on Router RT1

Source: Understanding Linux Network Internals

User-Level Networking APIs

- Programmers rarely create Ethernet frames
  - Or IP or TCP packets
- Most applications use the ***socket*** abstraction
  - Stream of messages or bytes between two applications
  - Applications specify protocol (TCP or UDP), remote IP address and port number
- `socket()`: create a socket; returns associated file descriptor
- `bind()/listen()/accept()`: waits for incoming connection (*server*)
- `connect()`: connect to remote end (*client*)
- `send()/recv()`: send and receive data
  - All headers are added/stripped by OS

Linux Implementation

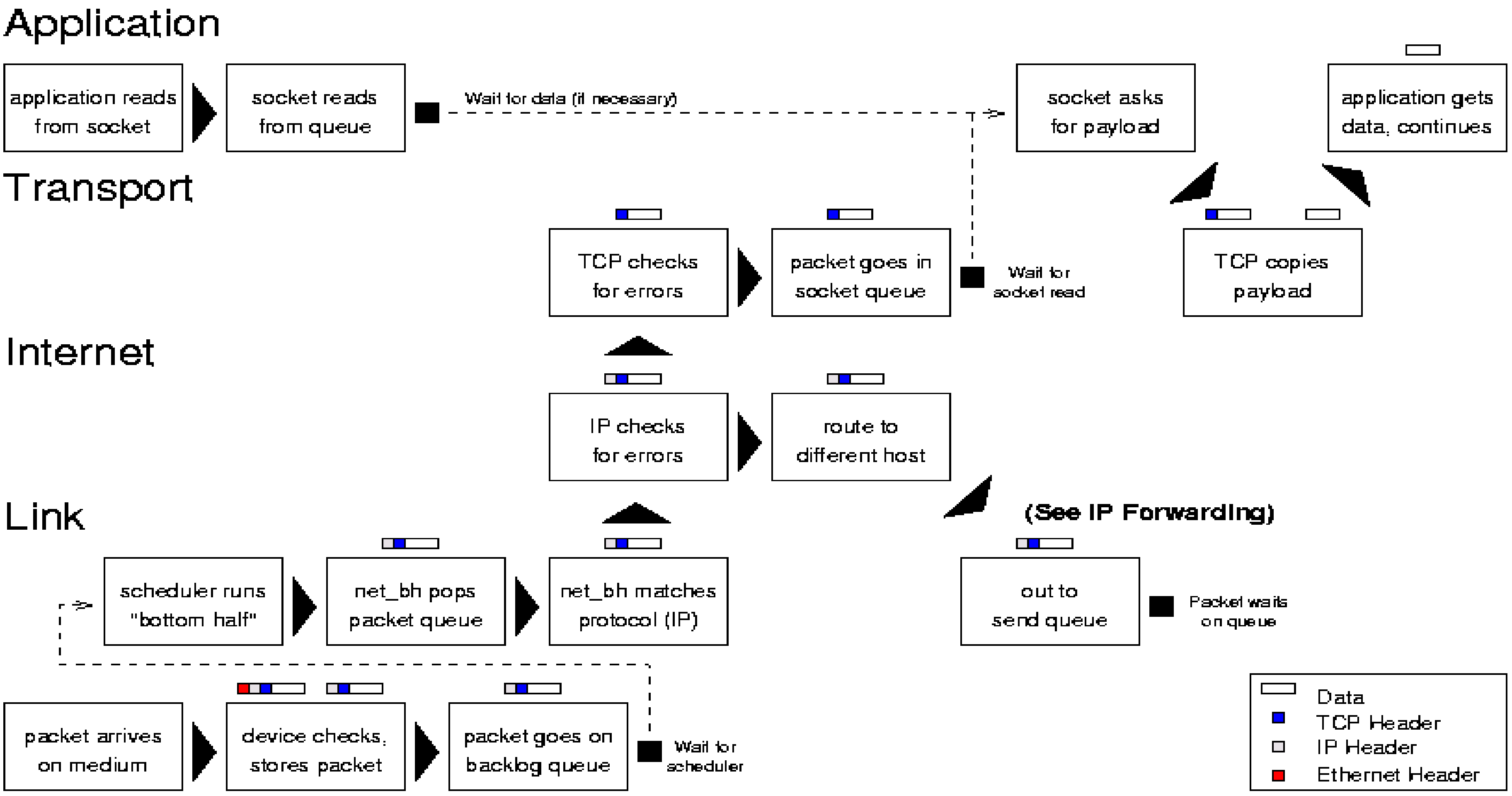
- Sockets implemented in the kernel
  - So are TCP, UDP, and IP
- Benefits:
  - Application not involved in TCP ACKs, retransmit, etc.
    - If TCP is implemented in library, app wakes up for timers
  - Kernel trusted with correct delivery of packets
- A single system call:
  - `sys_socketcall(call, args)`
    - Has a sub-table of calls, like bind, connect, etc.

Other Networking Services in Linux

- In addition to the socket interface, the kernel provides a ton of other services
  - Bridging (L2 switching)
  - Loopback and virtual network devices
  - Routing (L3 switching)
  - Firewall and filtering
  - Packet sniffing
  - …
- We only focus on general packet processing for application send and receives

(Part of) Received Packet Processing

Source: *http://www.cs.unh.edu/cnrg/people/gherrin/linux-net.html*



Application

application reads from socket

socket reads from queue

Wait for data (if necessary)

socket asks for payload

application gets data, continues

Transport

TCP checks for errors

packet goes in socket queue

Wait for socket read

TCP copies payload

Internet

IP checks for errors

route to different host

(See IP Forwarding)

Link

scheduler runs "bottom half"

net_bh pops packet queue

net_bh matches protocol (IP)

out to send queue

Packet waits on queue

packet arrives on medium

device checks, stores packet

packet goes on backlog queue

Wait for scheduler

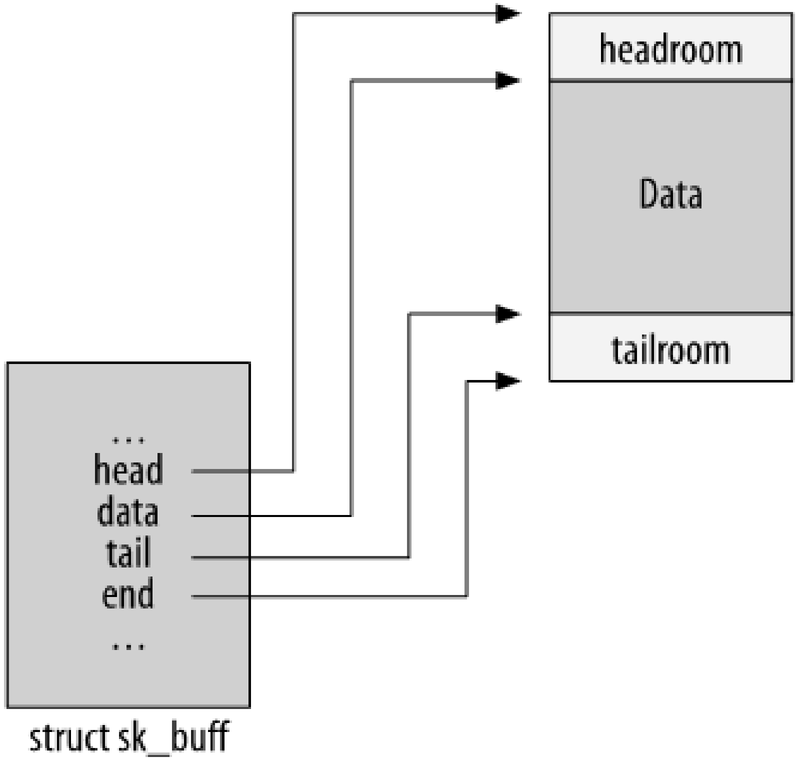
- ▭ Data
- 🟦 TCP Header
- ⬜ IP Header
- 🟥 Ethernet Header

Linux Plumbing

- Each message is put in a `sk_buff` structure
  - Passed through a stack of protocol handlers
  - Handlers update bookkeeping, wrap headers, etc.
- At the bottom is the device itself (e.g., NIC driver)
  - Sends/receives packets on the wire

Efficient Packet Processing

- Receive side:
  Moving pointers is better than removing headers
- Send side:
  Prepending headers is more efficient than re-copy



head/end vs. data/tail pointers in sk_buff

Source: Understanding Linux Network Internals

Interrupt Handler

- “Top half” responsible to:
  - Allocate/get a buffer (`sk_buff`)
  - Copy received data into the buffer
  - Initialize a few fields
  - Call “bottom half” handler

- For modern devices:
  - Systems allocate ring of `sk_buffs` and give to NIC
  - Just “take” the buff from the ring
    - No need to allocate (was done before)
    - No need to copy data into it (DMA already did it)

Software IRQs (1)

- A hardware IRQ is the hardware interrupt line
  - Use to trigger the *top half* handler from IDT
- Software IRQ is the big/complicated software handler
  - You know it as the *bottom half*
- Why separate top and bottom halves?
  - To minimize time in an interrupt handler with other interrupts disabled
  - Simplifies service routines (defer complicated operations to a more general processing context)
    - E.g., what if you need to wait for a lock?
    - or, be put to sleep until your `kmalloc()` succeeds?
  - Gives kernel more scheduling flexibility

Software IRQs (2)

- How are these implemented in Linux?
  - Two canonical ways: ***Softirq*** and ***Tasklet***
  - More general than just networking
- There is a per-cpu bitmask of pending Soft-IRQs
  - One bit per Soft IRQ (e.g., NET_RX_SOFTIRQ and NET_TX_SOFTIRQ for network receive and send)
  - There is a (function, data) tuple associated with each Soft IRQ
- Hard IRQ service routine sets the bit in the bitmask
  - The bit can also be set by other code in the kernel including Soft IRQ code itself
- At the right time, the kernel checks the bitmask and calls `function(data)` for pending Soft IRQs
  - Right time: Return from exceptions/interrupts/syscalls
  - Each CPU also has a kernel thread ***ksoftirqd<CPU#>***
    - Processes pending bottom halves for that CPU
    - ***ksoftirqd*** is nice +19: Lowest priority—only called when nothing else to do

Softirq

- Only one instance of softirq will run on a CPU at a time
  - If interrupted by HW interrupt, will not be called again
  - Guaranteed that invocation will be finished before start of next
- One instance can run on each CPU concurrently
  - Need to be thread-safe
    - Must use locks to avoid conflicting on data structures

Tasklet

- Special form of softirq
  - For the faint of heart (and faint of locking prowess)
- Constrained to only run one instance at a time on any CPU
  - Useful for poorly synchronized device drivers
    - Those that assume a single CPU in the 90’s
  - Downside: All tasklets are serialized
    - Regardless of how many cores you have
    - Even if processing for different devices of the same type
      - e.g., multiple disks using the same driver

Back to Receive: Bottom Half

- For each pending `sk_buff`:
  - Pass a copy to any taps (sniffers)
  - Do any MAC-layer processing, like bridging
  - Pass a copy to the appropriate protocol handler (e.g., IP)
    - Recur on protocol handler until you get to a port number
      - Perform some handling transparently (filtering, ACK, retry)
    - If good, deliver to associated socket
    - If bad, drop

Socket Delivery

- Once bottom half moves payload into a socket:
  - Check to see if a task is blocked on input for this socket
    - If yes, wake it up
- Read/recv system calls copy data into application

Socket Sending

- Send/write system calls copy data into socket
  - Allocate `sk_buff` for data
  - Be sure to leave plenty of head and tail room!
- System call handles protocol in application's timeslice
  - Receive handling not counted toward app
- Last protocol handler enqueues packet for transmit
  - If there is space in the TX ring
- Interrupt usually signals completion
  - Interrupt handler frees the `sk_buff`
  - Also, adds pending packets to the TX ring if previously full

Receive Livelock

- What happens when packets arrive at a very high frequency?
    - You spend all of your time handling interrupts!
- Receive Livelock: Condition when system never makes progress
    - Because spends all of its time starting to process new packets
    - Bottom halves never execute
        - Hard to prioritize other work over interrupts
- Better process one packet to completion than to run just the top half on a million

Receive Livelock in Practice

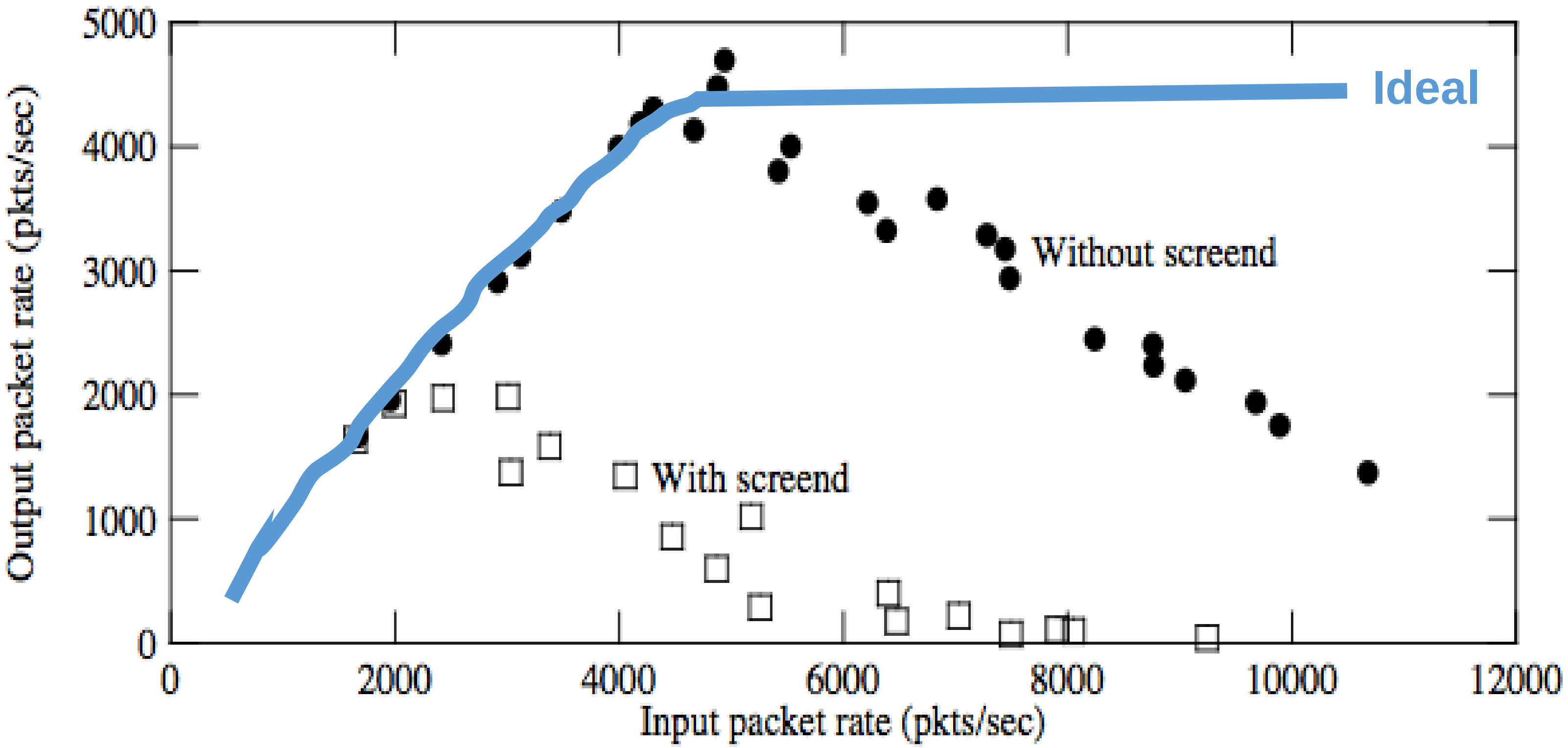


Fig. 2. Forwarding performance of unmodified kernel.

Source: Mogul & Ramakrishnan, ToCS, Aug 1997

Shedding Load

- If can’t process all incoming packets, must drop some
- If going to drop some packets, better do it early!
    - Stop taking packets off of the network card
    - NIC will drop packets once its buffers get full on its own

Polling Instead of Interrupts

- Under heavy load, disable NIC interrupts
- Use polling instead
  - Ask if there is more work once you’ve done the first batch
- Allows packet go through bottom half processing
  - And the application, and then get a response back out
- Ensures some progress

Why not Poll All the Time?

- If polling is so great, why bother with interrupts?
- Latency
  - If incoming traffic is rare, want high-priority
    - Latency-sensitive applications get their data ASAP
    - Example: annoying to wait at ssh prompt after hitting a key

General Insight on Polling

- If the expected input rate is low
  - Interrupts are better
- When expected input rate is above threshold
  - Polling is better
- Need way to dynamically switch between methods

Why Only Relevant to Networks?

- Why don’t disks have this problem?
  - Inherently rate limited
- If CPU is too busy processing previous disk requests
  - It can’t issue more
- External CPU can generate all sorts of network inputs

Linux NAPI (*New API*)

- Drivers provides `poll()` method for low-level receive
  - Passes packets received by the device to kernel
- Bottom half (softirq) calls `poll()` to get pending packets from the device
  - Can disable the interrupt under heavy loads
    - Or use a timer interrupt to schedule a poll
  - Bonus: Some NICs have a built-in timer
    - Can fire an interrupt periodically, only if something to say!
- Gives kernel control to throttle network input
  - Under heavy-load, device will overwrite some packets
    - Packets dropped in the device itself without involving the CPU